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Assessment of Passive Solar Atrium Designs

Leslie Jones and Associates Inc.

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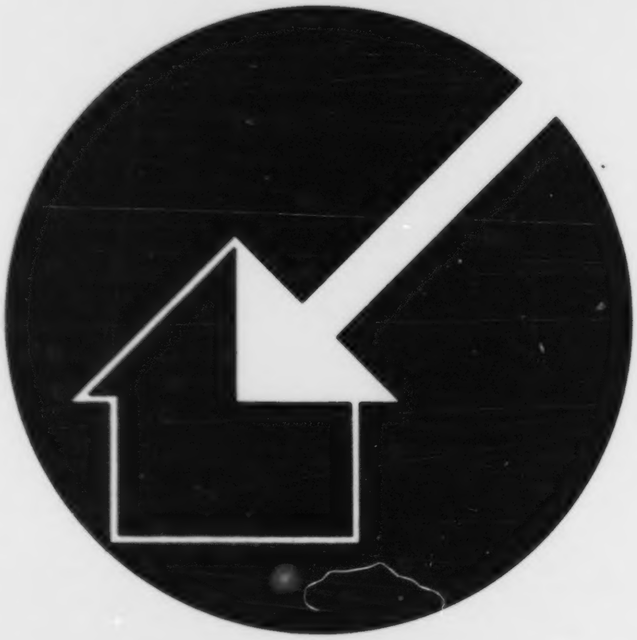

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ASSESSMENT OF PASSIVE SOLAR
ATRIUM DESIGNS

FINAL REPORT
PROJECT SUMMARY

DSS FILE NO. 04SR.31926-4-5018

August, 1985

Leslie Jones and Associates Inc.

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ABSTRACT

This report has been prepared with the intent of aiding architects and engineers with the planning and design of Atrium Buildings. This aid comes in five principal areas, each covered by a separate section in the report as follows:

1. An overview of design issues which could serve as a design checklist or primer.
2. A detailed evaluation of a number of these design issues.
3. A cost study comparison aimed at highlighting differences between atrium and non-atrium buildings.
4. Details of how currently available software can be applied to modelling a variety of Atrium features.
5. A Bibliography providing a comprehensive source of reference material for further reading.

RÉSUMÉ

Le présent rapport a été préparé afin d'aider les architectes et ingénieurs lors de la planification et de la conception de bâtiments avec atriums. Chacune des sections du rapport porte sur un des cinq grands domaines suivants:

1. Un survol des éléments de conception qui pourrait servir de liste de vérification ou d'introduction à la conception.
2. Une évaluation détaillée d'un certain nombre de ces éléments de conception.
3. Une étude comparative des coûts visant à souligner les différences entre les bâtiments avec et sans atriums.
4. Une analyse détaillée de l'utilisation des logiciels disponibles pour la simulation des caractéristiques des atriums.
5. Une bibliographie fournissant une source complète de documents de référence pour une lecture plus approfondie.

1. OVERVIEW OF DESIGN ISSUES

1.1 Introduction

The aim of this section is to present an overview of design issues as they relate to the design and planning of atriums or buildings containing atria. It is not the intent to reproduce standard design information in this text, but to raise those features that are unique to, or expressly pertinent to atrium buildings.

The work presented is based on a review of literature dealing with atriums. The views expressed are in most cases those views expressed in the literature and not necessarily views held by the writers of this report.

A complete listing of the literature reviewed is given in Section 5 where each reference has been keyworded to indicate the subject areas of the text. The keywords used there correspond with the subject areas discussed below.

References throughout the text are made to one, two, three and four sided atriums and to linear atriums, the definition of which are illustrated in Figure 1.1.

FOR A CLEARER UNDERSTANDING OF THE TEXT IT IS IMPORTANT FOR THE READER TO BE FAMILIAR WITH THIS TERMINOLOGY.

1.2 Planning for Low Energy Use

A number of opportunities for energy effectiveness and energy related issues are discussed in the literature and a summary of the most important are presented below:

i) Minimisation of exposed envelope area. Compact buildings have less skin area and consequently less heat losses and gains than do tower buildings of the same size. This, of course, would apply equally well, possibly moreso, to compact form buildings without atria.

ii) The use of the atriam as a "Buffer" area. Atria can be used as a buffer between the external environment and the main occupied space. The energy advantage of such a strategy is, however, progressively lost as the level of conditioning of the atrium space reaches that of the main occupied space.

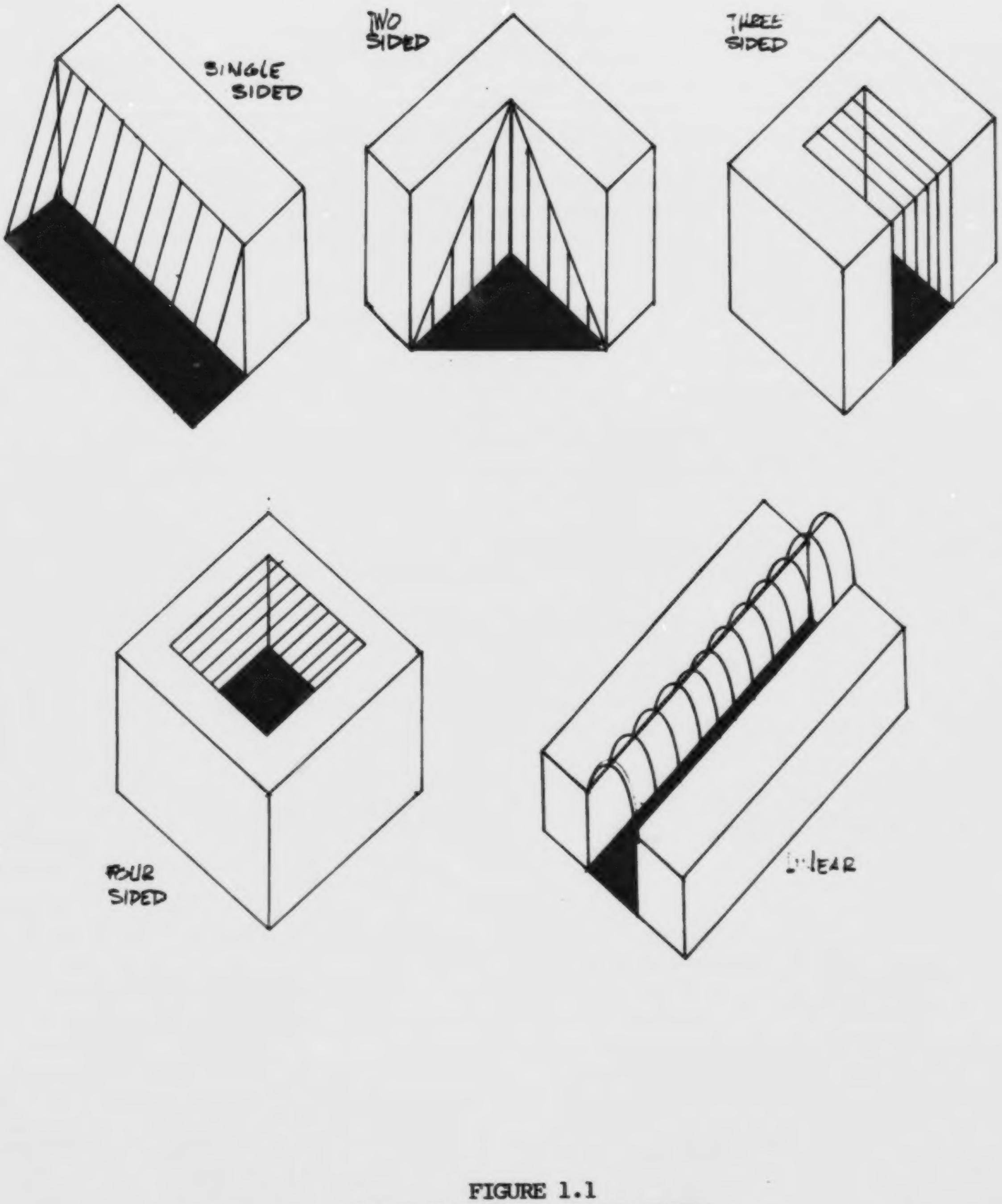

SINGLE SIDED
TWO SIDED
THREE SIDED
FOUR SIDED
LINEAR

FIGURE 1.1
ILLUSTRATION OF ATRIUM TYPES

iii) The use of the atrium as a solar collector. Solar gains collected in the atrium space can be utilised in the main occupied space without the problems associated with direct gain strategies (i.e., glare and thermal discomfort). This effect is greatest if the temperature of atrium space is not closely controlled.

iv) Lower infiltration rates. Low buildings have lower wind and stack induced infiltration losses than do equivalent size tower buildings. The lack of internal partitioning in the atrium building will however tend to offset this benefit somewhat.

v) Loss of sunlight and daylight. Utilising more of the site by building deeper plan structures in urban settings will mean that the exterior walls and windows are likely to be more shaded than a tower equivalent and this may have an adverse potential on the energy use of the facility.

vi) Solar shading requirements. If the atrium is used to collect solar gains for winter heating some form of summer shading will be desirable. Because of the seasonal time lag between maximum solar radiation and maximum air temperatures fixed shading is not considered beneficial, i.e., if the shading system prevents solar from entering the atrium in September and October in order to minimise cooling loads, it will in turn reject solar radiation when it would probably be beneficial in February and March.

vii) Level of comfort conditioning. Relaxing environmental criteria in the atrium space or eliminating climate control completely will reduce the overall building consumption but subject to the conditions maintained in the space, may compromise the usefulness of the space. Relaxing atrium conditions becomes inappropriate if the adjoining spaces are left open to the atrium.

viii) Atrium shape and size. Increasing the size and changing the geometry of the atrium and main building for increased daylight penetration and for collection of passive gains could be offset by possible increased heating and cooling loads.

ix) Envelope insulation and glazing strategies. Levels and location of insulation, type of glazing and glazing placement, shading strategies, amount and placement of mass, movable insulation devices, all require evaluation in the light of the level and quality of conditioning in the atrium space. E.g., for heated atria double glazing is better placed on the exterior atrium wall than on the interior wall (assuming only one of the walls will be double glazed and the other single glazed.) The reverse is true of unheated atria.

x) Daylighting opportunities. Opportunities exist for the daylighting of occupied spaces facing into the atrium as well as for the atrium space itself.

xi) Temperature stratification in the atrium. Opportunities exist for capitalising on air stratification in high atrium spaces.

1.3 Modelling

Current energy analysis software has not been specifically designed for the analysis of atriums in large buildings and as such application to these buildings requires careful use and special techniques.

Modelling weaknesses that are fairly specific to modelling atrium buildings, as opposed to general modelling weaknesses, are briefly presented below. The topic of modelling is discussed more fully in Section 4.

i) Solar radiation passing directly through the atrium space and into the adjoining space. Most programs do not have the facility for modelling solar radiation gains through interior partitions; i.e. through the interior atrium glazing. The use of movable shading devices on the "interior" atrium walls makes this aspect even more complex.

ii) Radiant heat exchange. Difficulties associated with the solution of heat exchanges resulting from absorbed solar radiation within complex geometric shapes are not normally rigorously addressed.

iii) Interzone air exchange. The modelling of mechanically or naturally induced air movement between zones and the modelling of HVAC systems configured to promote air mixing or pre-heating is not explicitly covered in currently available software.

iv) Temperature stratification. The calculation of stratification temperatures within the atrium and the varying effect that these temperatures have on heat flow to and from the adjoining space at different levels is not generally accommodated. The problem is further complicated by the flow of outside air through the space (i.e., infiltration and natural ventilation).

v) Daylighting. Complex geometrical shapes makes daylight prediction difficult. While modelling of daylight in the atrium space itself is probably not too critical since the visual task in this space is not likely to be severe, the prediction of daylight into the adjoining space will inevitably be problematic.

vi) Glare. As with daylighting complex geomtric shapes makes the prediction of daylight glare in both the atrium and adjoining space difficult.

1.4 HVAC Design

1.4.1 System Approaches

There are three basic approaches to heating, air conditioning or ventilating atrium buildings:

i) To treat the atrium as a completely independent space with no thermal mixing with other zones.

ii) To aid heat flow to or from the atrium without the direct transfer of air, e.g. using heat pumps or heat exchangers.

iii) To freely mix or transfer air between the atrium and other zones, i.e. to promote thermal mixing as and when it is desirable to do so.

Transferring of air as in iii) above can be achieved by:

i) Using the atrium space as a return plenum or,
ii) Using the atrium space as a supply plenum or,
iii) Drawing outside air through the atrium or,
iv) Passing exhaust air through the atrium

The four methods along with possible variations and notes on their applicability are given in Figures 1.2 to 1.5.

1.4.2 Thermal Stratification in the Atrium

Thermal stratification can be ignored, accommodated, i.e. its adverse effects minimised, or capitalised upon.

In winter, warm air from top of atrium can be recirculated back to atrium floor using propeller fans, tubes or air entrainment; or returned directly back to HVAC plant (see Figure 1.6). To entrain hot air successfully, it is necessary to supply from a high level. This also has the advantage of minimising the risk of cold down drafts caused by injecting air at low level. Unfortunately, projecting hot air downwards for long distances is made difficult since one is working against the natural buoyancy of hot air. Further, supplying from a high level is not consistent with the desired summer operation.

In summer, a reservoir at the top of the atrium, above the top of occupied space, will limit the temperature difference that would otherwise be experienced across the upper atrium walls (see Figure 1.7). To minimise cooling or limit cooling loads it is desirable to avoid entraining hot air from the top of the atrium by supplying air at low levels.

1.4.3 Other Issues

.1 If the atrium is to be treated as a separate independent zone, natural ventilation may be considered as an alternative to mechanical cooling.

.2 There may be cost and operational advantages to using the HVAC equipment for the purposes of smoke control and ventilation (see Section 1.9).

.3 Where a narrow building plan around a central or linear atrium is used it may be practical to do all comfort conditioning of the attached space from ducts located in the atrium, and exposed if considered aesthetically acceptable, eliminating the need for dropped ceilings in the main occupied space (see Figure 1.8).

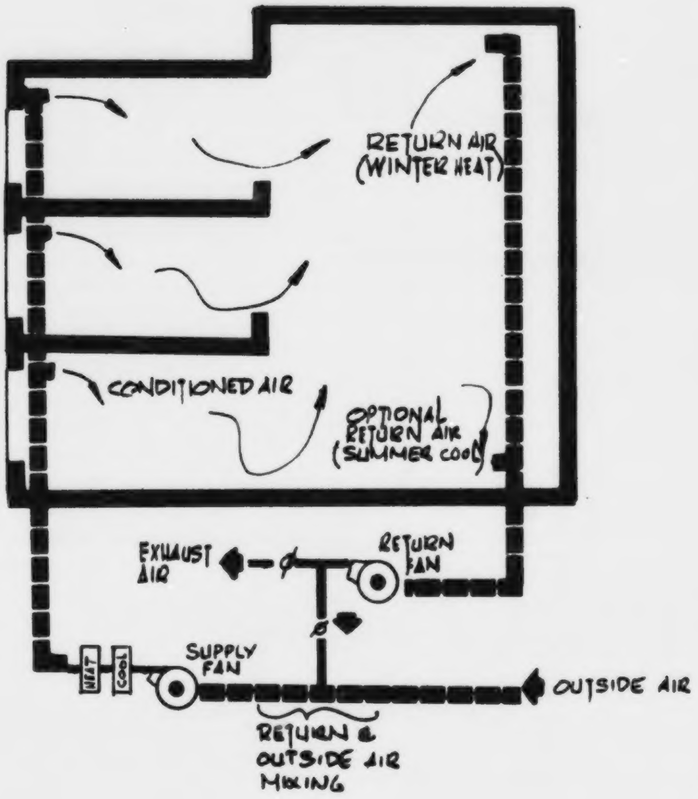
1.5 Electric Lighting Design

1.5.1 Lighting of the Atrium Space

Lighting considerations of particular relevance to the atrium space include:

i) The possible need to provide light sources to complement daylight sources to maintain healthy plant growth and to provide acceptable colour appearance of plants (see also 1.12 on planting).

ii) The use of high wattage, high efficiency, long life sources in high atriums for good energy economy and minimisation of lamp changes. Suggested sources are metal halide, ceramalux (high pressure sodium) and mercury vapour. Combinations can be used to advantage for good colour appearance.


RETURN AIR
(WINTER HEAT)
CONDITIONED AIR
OPTIONAL
RETURN AIR
(SUMMER COOL)
EXHAUST
AIR
RETURN
FAN
HEAT
COOL
SUPPLY
FAN
OUTSIDE AIR
RETURN &
OUTSIDE AIR
MIXING

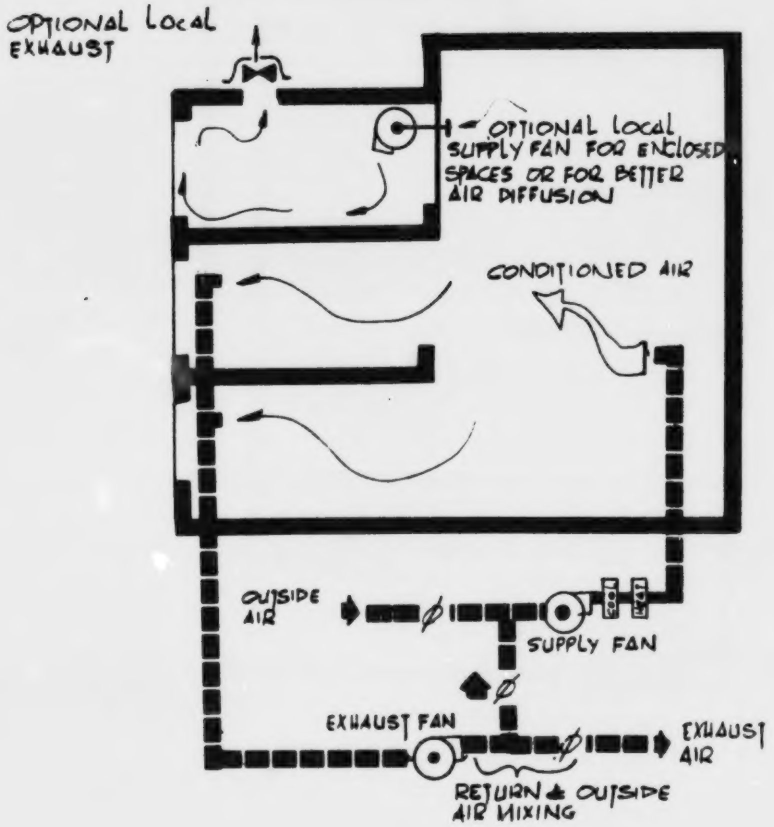
ADVANTAGES

- Excess heat in the main occupied space is used for atrium heating & vice versa.
- Consistent with use of atrium for smoke clearance, return fan for smoke vent.
- Consistent with stratification strategies.
- Reduced ductwork cost & space requirements (return duct mainly omitted).

DISADVANTAGES

- Applicable for conditioned atria only.
- Atrium space gets second hand air

FIGURE 1.2
THE ATRIUM AS A RETURN PLENUM


OPTIONAL LOCAL EXHAUST
OPTIONAL LOCAL SUPPLY FAN FOR ENCLOSED SPACES OR FOR BETTER AIR DIFFUSION
CONDITIONED AIR
OUTSIDE AIR
SUPPLY FAN
EXHAUST FAN
EXHAUST AIR
RETURN & OUTSIDE AIR MIXING

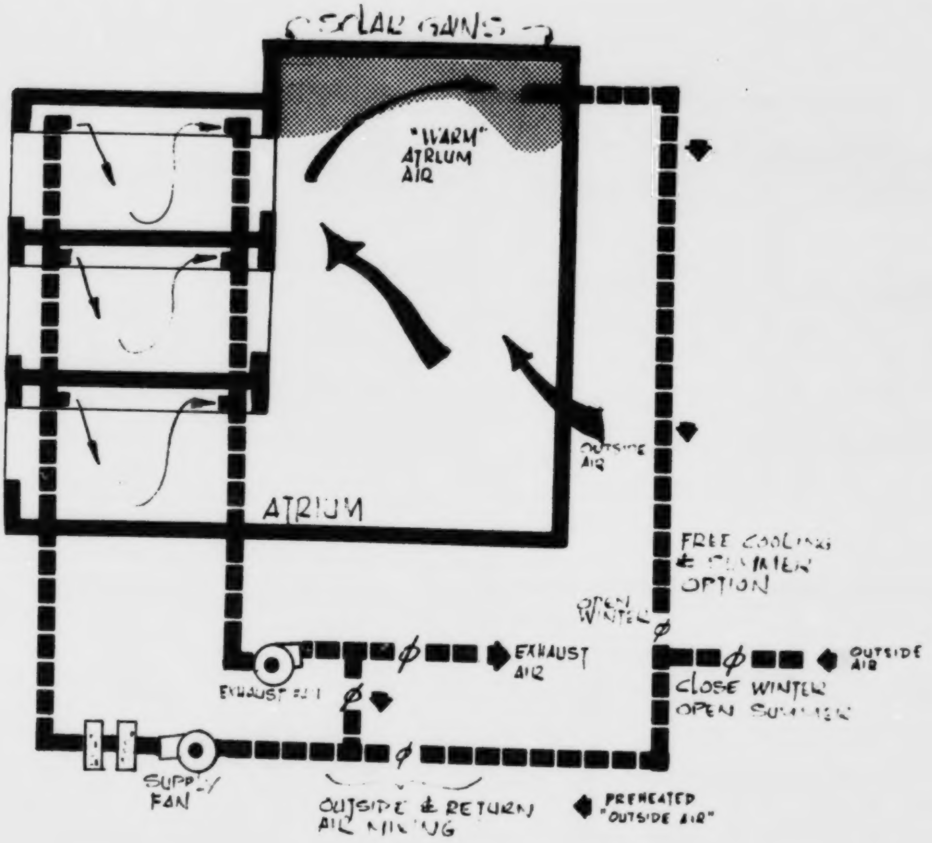
ADVANTAGES

- Local supply fans can be used for individual room control (system used at Atlanta Regency Hotel).
- Simplified ductwork system, lower pressure drops than with fully ducted system, more so than with atrium serving as return plenum.

DISADVANTAGES

- Applicable for conditioned atria only.
- Main occupied space gets second hand air.
- Requires additional smoke vent fan in atrium.

FIGURE 1.3
THE ATRIUM AS A SUPPLY PLENUM


SOLAR GAINS
"WARM" ATRIUM AIR
OUTSIDE AIR
ATRIUM
FREE COOLING & SUMMER OPTION
OPEN WINTER
EXHAUST AIR
EXHAUST FAN
OUTSIDE AIR
CLOSE WINTER OPEN SUMMER
SUPPLY FAN
OUTSIDE & RETURN AIR MIXING
PREHEATED "OUTSIDE AIR"

ADVANTAGES

- Potential energy saving winter operation.

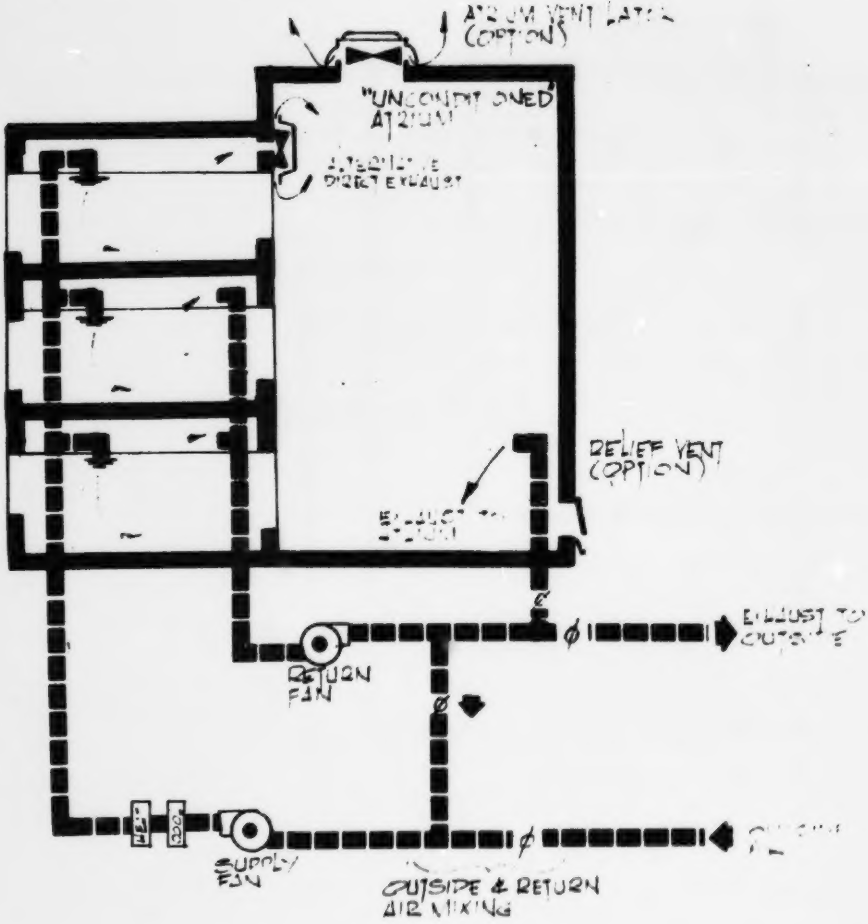
DISADVANTAGES

- For unconditioned (buffer or canopy) atria only.
- Optional dampers required for periods when pre-heated air would increase summer cooling load.

OPTION - Provide access to outside air directly for when building can make use of free cooling.

ALTERNATIVE - is to pass uninsulated duct carrying outside air through atrium at high level to pick up solar heat.

FIGURE 1.4
PREHEATING VENTILATION AIR IN THE ATRIUM


ATRIUM VENTILATOR
(OPTION)
"UNCONDITIONED"
ATRIUM
ALTERNATIVE
DIRECT EXHAUST
RELIEF VENT
(OPTION)
EXHAUST TO
ATRIUM
EXHAUST TO
OUTSIDE
RETURN
FAN
HEAT
COOL
SUPPLY
FAN
OUTSIDE & RETURN
AIR MIXING

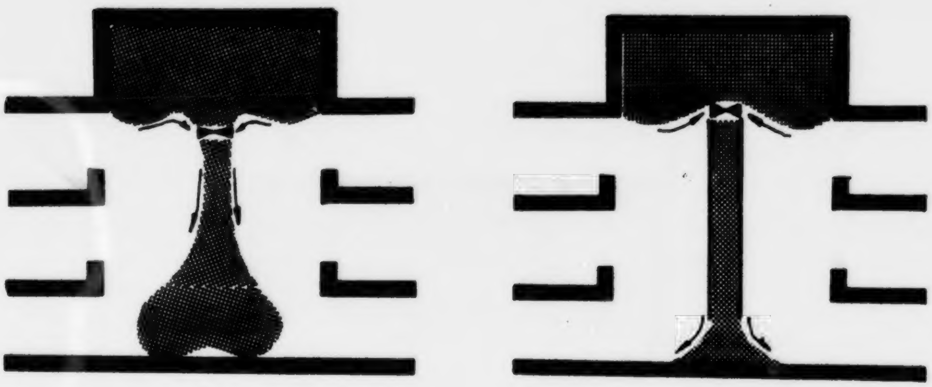
ADVANTAGES

- Can provide some cooling of atrium space during warmest periods.
- Can provide some heating of atrium space in winter.
- Supplementary static heating can be used as additional heat source.

DISADVANTAGES

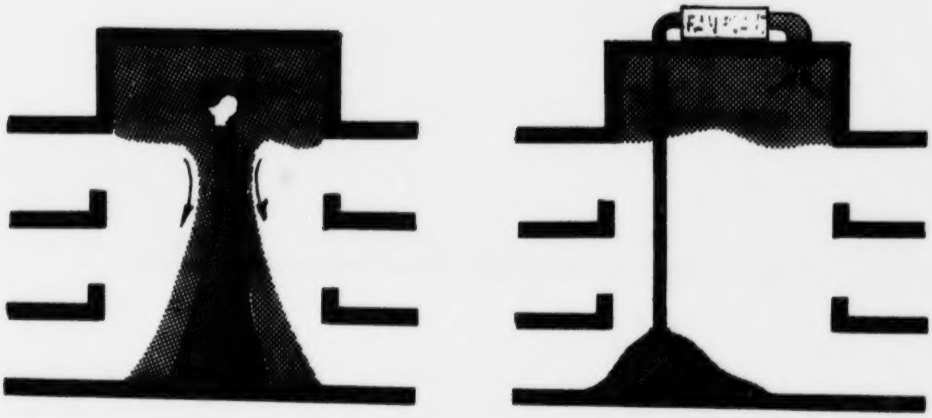
- Atrium receives second hand air.
- For unconditioned or heated only applications.
- In order to avoid overheating atrium when exhaust warmer than outside air, secondary vent system required for atrium.

FIGURE 1.5
EXHAUSTING AIR THROUGH THE ATRIUM



USING DESTRATIFICATION FANS

USING DESTRATIFICATION TUBES



BY INDUCING
WARM AIR

BY DRAWING WARM AIR
FROM TOP OF SPACE
USING FAN PLANT

FIGURE 1.6
DESTRATIFICATION STRATEGIES FOR WINTER HEATING

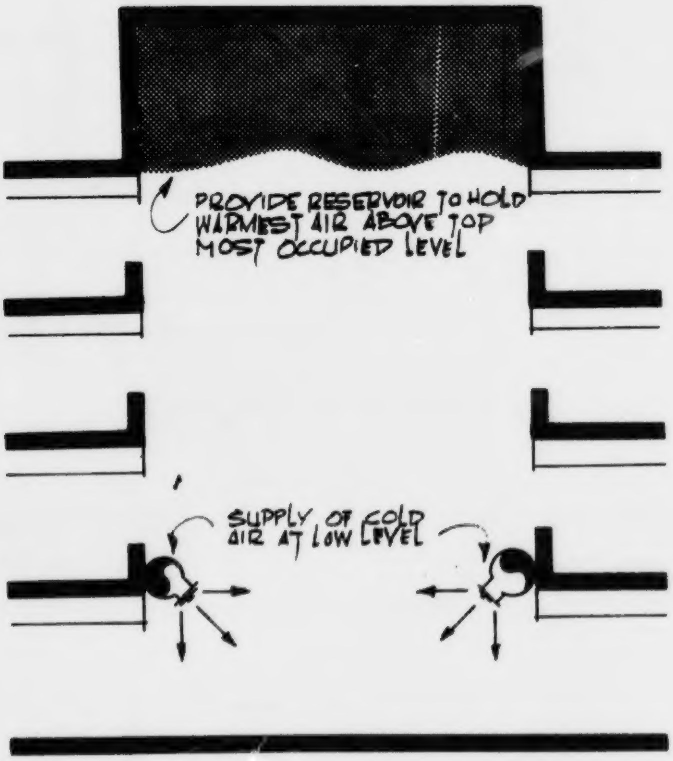

PROVIDE RESERVOIR TO HOLD WARMEST AIR ABOVE TOP MOST OCCUPIED LEVEL
SUPPLY OF COLD AIR AT LOW LEVEL

FIGURE 1.7
MAKING USE OF AIR STRATIFICATION TO MINIMISE SUMMER COOLING

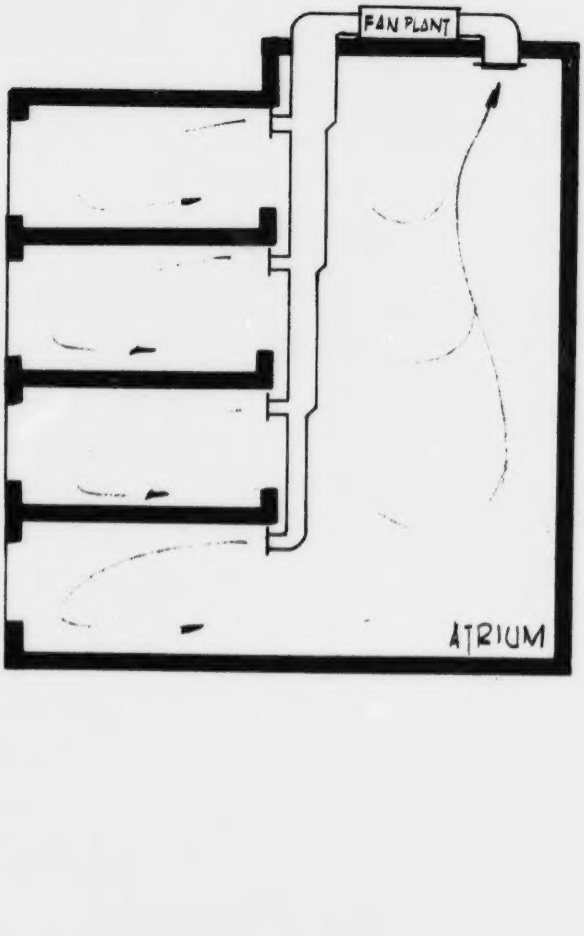

FAN PLANT
ATRIUM

FIGURE 1.8
USING THE ATRIUM SPACE AS A DUCTWORK ROUTE

iii) Switching or dimming of electric light with daylight level to minimise energy use. Because of the general lack of exacting visual task in atrium spaces, daylight switching can be cruder than in physically more demanding areas such as offices.

1.5.2 Lighting of the Adjoining Space

i) Minimising the direct view of the sky while still providing some daylight and a view can reduce the need for the high lighting levels required in deep plan offices which would otherwise be required to balance the brightness of the window.

ii) The use of "artificial daylighting" of the perimeter spaces using borrowed light from the atrium produced by high efficiency sources may be a useful alternative to less efficient light sources in the actual space.

iii) Depending upon the potential daylight contribution from the Atrium space, it may be beneficial to dim or switch lights in the adjoining space in sympathy with the available natural light.

1.6 Daylight Design

1.6.1 Glazing Geometry

Daylight contributions need to be evaluated along with the benefits of winter solar heat and penalty of summer solar gains. Primarily, from a daylighting point of view:

i) horizontal glazing gives most light per area of glazing; it is however, considered unsuitable in most of Canada because of snow cover (and is thermally undesirable from a thermal standpoint because of high summer and low winter solar gains).

ii) vertical or inclined glazing is difficult to accommodate without unduly increasing the volume of the enclosed space or by creating valleys, in the case of saw tooth or monitor skylights, which can fill up with snow.

1.6.2 Daylight Contribution to Adjoining Spaces

In addition to a significant portion of the atrium space lighting requirements which should be capable of being met by daylighting, areas surrounding the atrium have a potential for utilising daylighting.

If it is wished to take advantage of this potential to any significant extent, it will be worthwhile to consider:

i) Providing only sufficient glazing at each level (to the adjoining space) for the desired daylight contribution. This would mean that windows near the top of the atrium would be smaller than those at the bottom (see Figure 1.9). By only taking enough light at the top of the atrium, more is left for use at lower levels.

ii) Providing light reflecting surfaces in the atrium.

iii) By redirecting light by the use of fixed or adjustable louvers on the atrium glass, by using light shelves in the atrium wall, or by using other reflective devices.

iv) Avoiding extensive landscaping (i.e. planting) where it may interfere with the desired flow of light in the atrium and into adjoining spaces.

Very accurate prediction of the amount of daylight entering areas adjoining the atrium is probably not possible owing to the difficulty of predicting the inter-reflection of the light in the atrium itself. The use of physical models and an artificial sky is possible for appraising complex geometry problems.

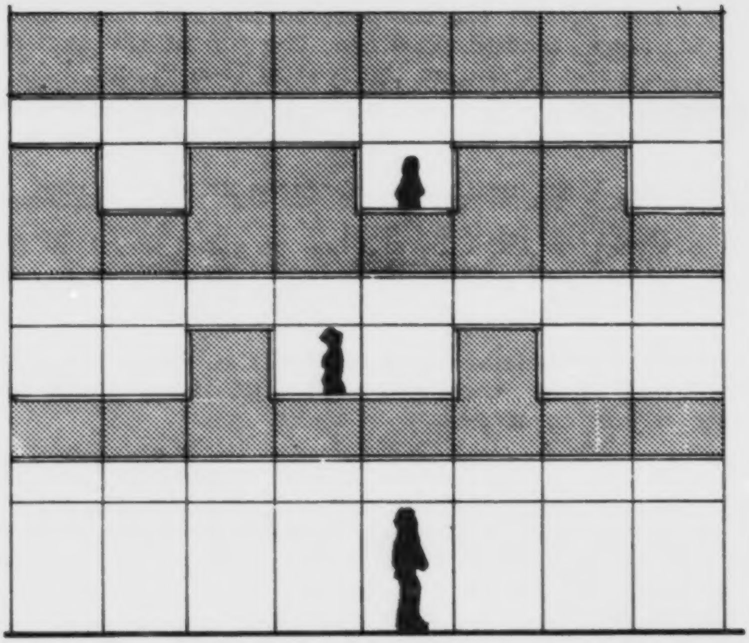


FIGURE 1.9
WINDOW GLAZING STRATEGY FOR ATRIUM PARTIONING

1.7 Fire Safety

Atriums have unique fire safety problems, principally because the normal practice of achieving fire safety through the compartmention of the building to minimise fire and smoke spread is abandoned in such buildings, i.e., the problem is one of fire and smoke spread through large unenclosed spaces. This and other problems particularly pertinent to atrium buildings are discussed below.

1.7.1 Fire Detection

Detection of smoke, which can travel quickly, needs to be rapid; detection based on thermal devices is generally considered unsatisfactory. This is particulary the case where smoke entering a large atrium from a fire in say an adjoining space is likely to be so cool as not to trigger thermal devices.

1.7.2 Fire Alarms

In large open spaces, especially where several of the occupants may be visitors, a voice annunciator type of fire alarm system is considered beneficial, particularly as it is often difficult to clearly mark exit routes in such spaces.

1.7.3 Fire and Smoke Constraint

Limiting the size of the fire and smoke production is generally considered an absolute necessity and most codes demand atrium buildings and buildings with large interconnected floor spaces (see 1.13 for definition) to be fully sprinkled.

Limiting the amount of combustibles in the actual atrium space is one way of minimising or preventing fires in these areas although this is not always compatible with the desire to use atrium spaces for temporary or permanent exhibits. Further, the regulation of such temporary exhibits is difficult.

Compartmentation can be used to constrain smoke and fire to its place of origin although this may be incompatible with the desire for open spaces. The separation of the atrium space from the remaining building floor area using glass, thereby preserving the view into the atrium, is a possible solution although most authorities agree that the integrity of the glazing, even if drenched with water using sprinklers, cannot be relied upon to any significant amount. There is also some concern that the use of drencher sprinklers to protect glazing could precipitate glass breakage due to thermal shock, especially where perfect drenching is not achieved.

Subject to the smoke control strategies used (see Section 1.7.4) the operation of the HVAC system should not aid the distribution and circulation of smoke and should be shut down as necessary. Fire and smoke dampers intended to prevent the spread of smoke should "fail" closed while those used to vent the smoke should "fail" open.

The use of baffles at ceiling level should be considered to slow down the horizontal movement of smoke. Such devices are particularly useful in linear type atriums. Such screens should be carried above false ceiling where the ceiling cannot be assured to be airtight. An example of the use of smoke screens is shown in Figure 1.10. Large volumes of smoke are typically produced even with quite small fires and such measures must be supplemented with a smoke ventilation system.

Fire spread from floor to floor in the space adjoining the atrium can be a problem. According to one reference the enclosing of the atrium walls results in less protection to fire spread (although potentially better for smoke spread) than does an open floor. Some codes, e.g. Canadian National Building Code, (NBC), call for close spaced sprinklers at openings to the atrium but in apparent contradiction to the above, not where the walls closed and glazed.

1.7.4 Smoke Ventilation

.1 Design Options

Because of the general limit on combustible materials imposed on the actual atrium space, it is normally assumed that the danger comes from fires in the adjoining spaces, not in the atrium itself.

There are three basic options as to the way in which smoke can be vented, namely;

i) to vent the smoke from the actual floor of the fire drawing air from the outside. Typically this would be done using the normal HVAC system operating on full fresh air.

ii) as i) but drawing air from the Atrium.

iii) to induce the smoke into and extracting it from the Atrium. In this case make up air would be supplied to the fire floor either directly from its HVAC system or indirectly from other floors.

These principals are illustrated in Figures 1.11, 1.12, and 1.13. Either mechanical or natural ventilation strategies may be pursued.

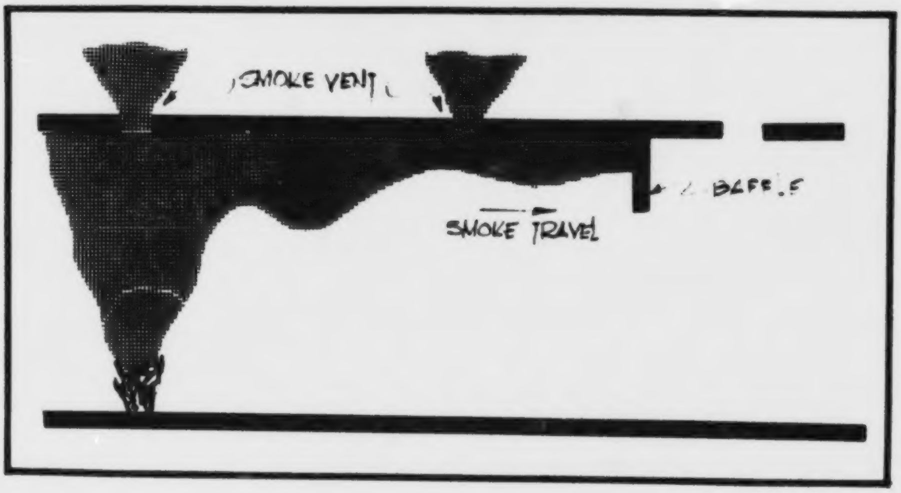
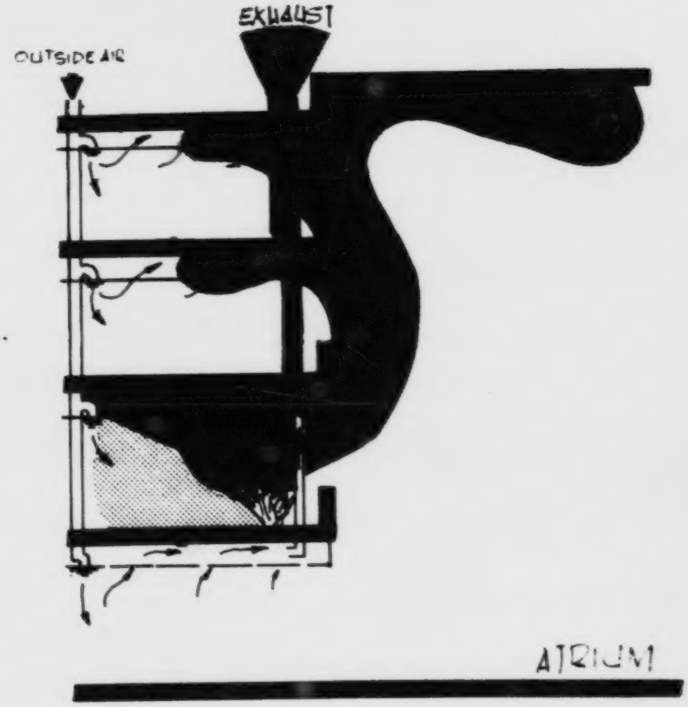

SMOKE VENT
BAFFLE
SMOKE TRAVEL

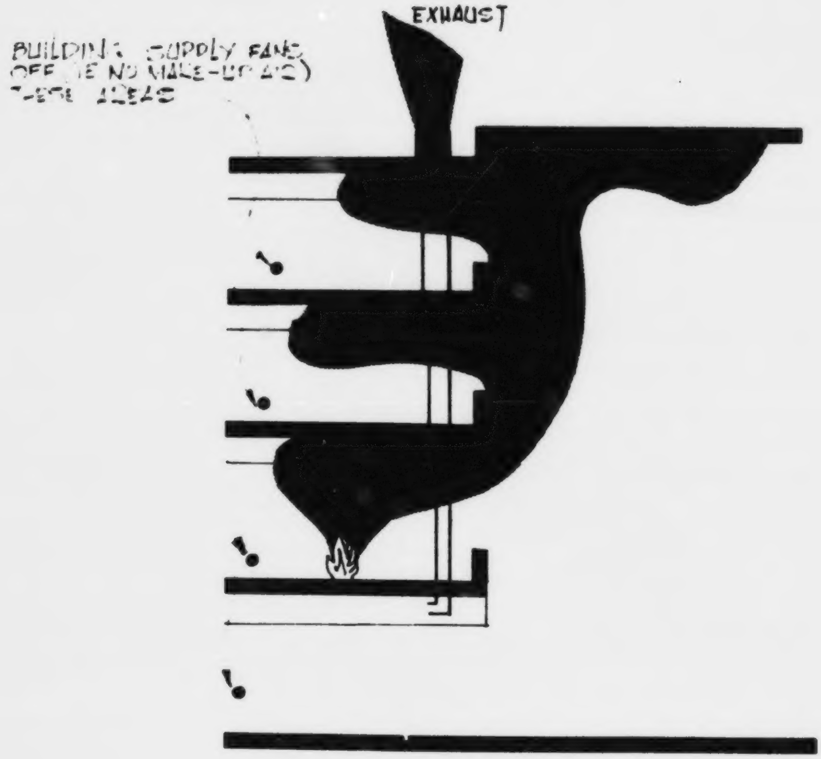
FIGURE 1.10
USE OF SMOKE SCREENS FOR LIMITING THE HORIZONTAL MOVEMENT OF SMOKE



ADVANTAGES
. No additional smoke vent equipment required.

DISADVANTAGES
. Unless very large floor spaces it is unlikely that the exhaust will be of sufficient capacity to vent fire-smoke. Therefore smoke will spill into atrium space and other floor areas.
. Normal HVAC supply air will mix smoke & could promote its spread to other occupied spaces.

FIGURE 1.11
SMOKE VENTILATION USING THE BUILDING HVAC SYSTEM


EXHAUST
BUILDING SUPPLY FANS OFF (IE NO MAKE-UP AIR) THESE AREAS

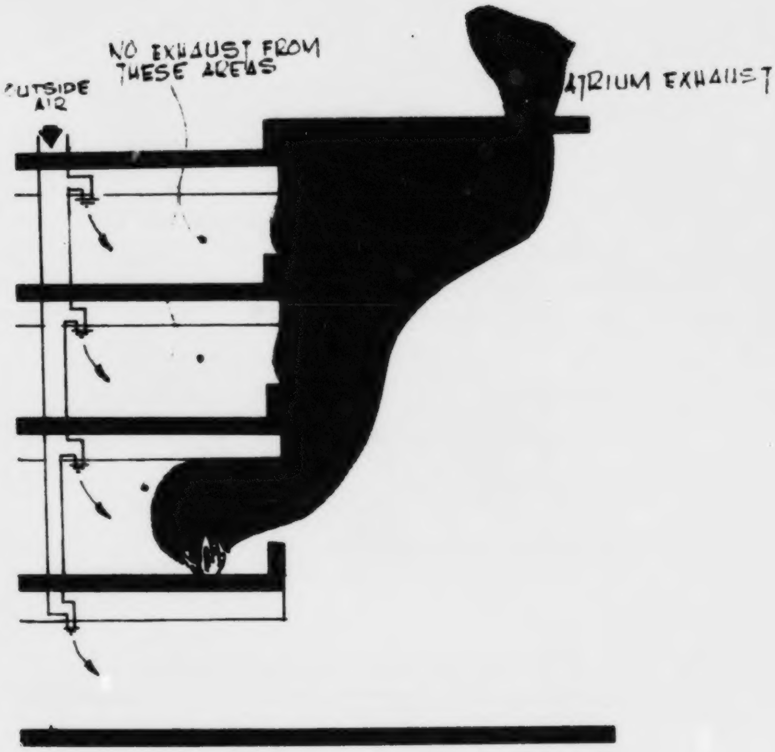
ADVANTAGES

- Atrium kept free of smoke.
- Additional Smoke Ventilation equipment may not be required.

DISADVANTAGES

- Unless very large floor spaces it is unlikely that the exhaust will be of sufficient capacity to vent the smoke. Therefore smoke will spill into the top of atrium and into main occupied spaces. Supplying air to non-fire floors may minimise smoke flow into occupied spaces.

FIGURE 1.12
SMOKE VENTILATION AT THE FIRE SOURCE DRAWING AIR FROM THE ATRIUM


NO EXHAUST FROM THESE AREAS
OUTSIDE AIR
ATRIUM EXHAUST

ADVANTAGES

. Supply to the main occupied space should minimise smoke transfer to these areas.

. If the atrium space is large, as compared to the rest of building and if the atrium exhaust is part of atrium HVAC or vent system it may provide required smoke vent rate.

DISADVANTAGES

. Smoke dampers required in all return air ductwork in main occupied space.

. Smoke in Atrium

FIGURE 1.13
SMOKE VENTILATION THROUGH THE ATRIUM SPACE

.2 Natural Ventilation

Despite an often widespread belief in the "fail-safe" characteristics of natural ventilation systems, mechanical ventilation is generally considered preferable to natural vent for the following reasons:

i) If the volume of the atrium is large with respect to smoke volume, smoke may become sufficiently diluted and cooled to prevent a fully functioning natural stack vent system from establishing itself. This condition would be aggravated in a cooled atrium under hot ambient conditions.

ii) Natural ventilation is susceptible to wind disturbance. This may be particularly troublesome where adjacent higher buildings or higher parts of the same building could channel wind down onto a lower roof.

iii) Larger damper-vent areas, relative to that required with mechanical vent are likely to increase air infiltration. If natural ventilation is used, the means of operating louvres and dampers should not be by thermal links as these are unlikely to function quickly enough (or not at all where the smoke is sufficiently cool).

iv) Inherent fail-safe operation of natural ventilation may be compromised by lack of maintenance preventing the unit from opening when required.

.3 Mechanical Ventilation

The following issues should be considered where a mechanical smoke ventilation system is to be designed:

i) Emergency only ventilation equipment may not function when required to do so. Regular maintenance and frequent testing would minimise this. (In one case a formal testing procedure was made part of the basis for a continuation of a hotel's occupancy permit.)

An alternative is to utilise the building HVAC system since a failure in this system is less likely to go unnoticed.

It is recommended that equipment for smoke vent be supplied from an emergency power source. If this is done, power requirements for the equipment where the main HVAC is the source of smoke vent are likely to be higher than if separate smoke exhaust equipment is used. If unitary HVAC equipment is used in the atrium, a means to separate and disconnect mechanical cooling function from the supply source will be required otherwise unrealistically high standby power generating sets will be needed.

ii) Clear instructions are required to instruct firemen how to operate smoke control equipment.

iii) Some codes require, as a rule of thumb, four to six atrium air changes per hour for smoke clearance. This is not always appropriate. For instance, if the atrium volume is small and used as a smoke channel, the atrium could very quickly become smoke-logged. In such cases the required vent rate may not be possible to obtain with the normal HVAC equipment and additional fans may be required.

iv) Cool smoke dropping to atrium floor, as with the case of natural vent, could compromise the success of the smoke vent system. One solution adopted to overcome this is to provide a mechanical means of blowing air up and inducing smoke from the atrium floor (see Figure 1.14).

v) If the atrium is used as a smoke channel (i.e. smoke exhausted through the atrium) and the atrium becomes smoke-logged there is a danger of smoke passing back into other occupied spaces. This could happen progressively from the top floors downwards. Ensuring a sufficiently high extract rate, providing a smoke reservoir at the top of the atrium, separating the adjoining spaces with glazing or other solid material (particularly the topmost floors) could prevent or minimise this occurrence.

vi) Where building HVAC systems are VAV types and are used for smoke ventilation, it will normally be necessary to ensure that the normal temperature control at the VAV boxes are bypassed and that the units open to full volume to ensure sufficient overall ventilation rate. Further it should be ensured that such normal safety features such as fan shut-down on low temperatures (to prevent coil freeze-up) are bypassed for the smoke ventilation mode.

vii) Generally speaking, it is generally desirable to supply make-up air at low levels to prevent or minimise the mixing of smoke. This may well be incompabible with typical HVAC air diffusion systems (i.e. supply and return at the ceiling).

1.7.5 Fire Suppression

As previously raised, buildings containing atriums or large interconnected floor spaces are required to be sprinkled in order to limit the size of a fire and the volume of smoke generated.

Sprinkling at high level in the atrium is considered by many to be undesirable because the sprinklers

i) are going to be slow to respond and may not, in fact, operate at all,

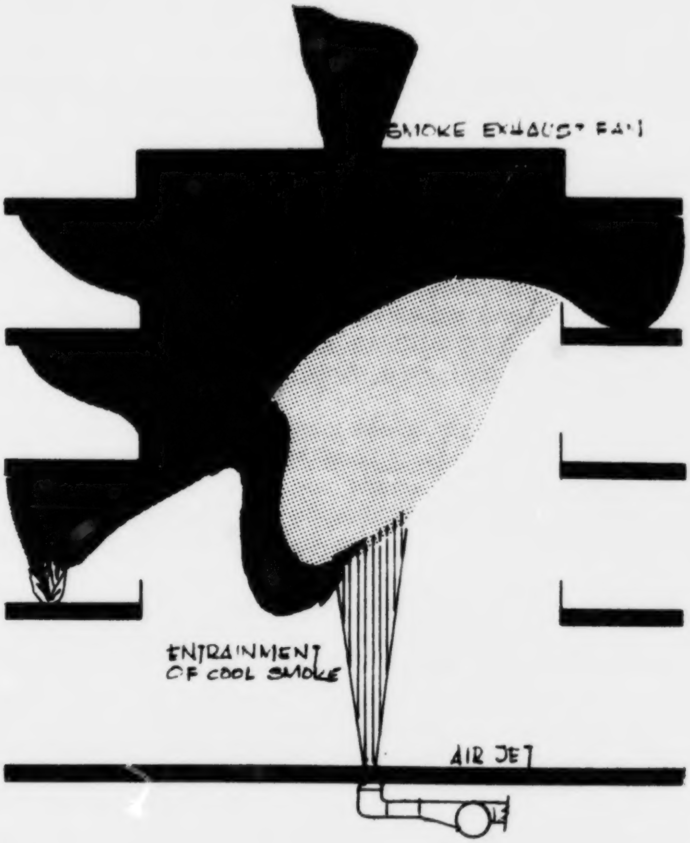

SMOKE EXHAUST FAN
ENTRAINMENT OF COOL SMOKE
AIR JET

FIGURE 1.14
MEANS OF PREVENTING COOL SMOKE DROPPING TO THE FLOOR OF THE ATRIUM

ii) should they operate, they would have an adverse effect on smoke ventilation by cooling and mixing the smoke and generally causing it to fall towards the floor.

Despite this, however, they are required by many codes including the Canadian National Building Code.

1.7.6 Means of Escape

Requirements for means of escape are normally specified in building codes and may in fact be more stringent for atrium buildings than for non-atrium buildings of a similar size (see Section .12)

Other considerations relevant to atria and other large spaces are:

i) Many of the occupants may be visitors unfamiliar with the building - consequently in the event of fire they are likely to use the route they know rather than a correct fire exit. Escape routes and exits need to be clearly identified, although this may be difficult in large spaces, especially where exit routes are obscured from view by features in the atrium.

ii) In long low atriums smoke can travel the length of the atrium, hit the end, and return back towards the fire. This can give a false impression of where the fire is located and could cause an occupant to head towards the fire. Smoke barriers and effective smoke ventilation will minimise such problems.

1.8 Structural Design Implications

The issues detailed below have been noted during the literature review.

i) Atrium buildings have been reported to be simpler structurally - this is generally a consequence of being simpler than an equivalent sized tower block rather than anything to do with the incorporation of an atrium into the design.

ii) In an atrium used for collecting and utilising solar gains in a passive fashion there may be some advantage in adopting a high mass (e.g. concrete and masonry) type of structure for the atrium spaces rather than using steel frame and lightweight curtain walls.

iii) The cost of providing round structural support for barrel vaulting and the like has been a significant disincentive to adopting circular as opposed to segmented glazing.

iv) There has been some argument precipitated by aesthetic considerations for the relaxation of requirements for the fire protection of structural steelwork in atria on the basis of the low fire risk in such areas.

v) Design of structures to support large areas of atrium glazing and for movable atrium roof coverings would appear to be areas of innovation of structural design.

1.9 Material & Envelope Systems

.1 Glazing Materials, Atrium

The choice of "glazing" materials range from conventional glasses through and rigid plastics to flexible fabric skins such as teflon and silicon coated glass fibre. "Glazing" may be fixed, openable or removable, clear or translucent. The actual choice of material requires considerations of and between their thermal and light transmission characteristics and their subsequent impact on heating, cooling and lighting in the building, and on capital costs.

Despite their major disadvantage of cumbustibility plastics have some advantages over glass for atrium glazing; namely:

i) Potentially lower cost, particularly over that of safety glass.
ii) Lower cost for curved sections.
iii) More resistent to damage, except by heat, than glass.
iv) Disadvantages of yellowing and surface scratchingand less optical clarity being minimised by new materials. Such effects are also less visible when viewed from afar (e.g. in an atrium skylight).
v) Colouring of plastic cheaper than colouring glazing - colour also minimises effect of yellowing and surface scratching.
vi) Coating is available to give selective transmission just as they are with glass.
vii) Composite, lightweight panels possible with low U-values.

If glass is to be used, annealed, heat-strengthened or tempered glass is safer than plate glass but laminated is preferred. Wired glass is accepted in single glazed instances but probably not appropriate in Canada except in unconditioned atria.

The potential formation of ice or condensation glazing, particularly where large swings in inside temperatures are permitted, requires some consideration.

.2 Air Tightness.

Since there are fewer internal restrictions to air movement in atrium buildings there is a special need to ensure a tight envelope to keep energy losses through stack effect to a minimum. Vestibules should be provided at all entrances and exits.

.3 Atrium Walls Construction.

Atrium walls, i.e. walls between the atrium and the main occupied space, need not be weatherised.

.4 Removable Envelope Components.

Fixed envelope components imply a need for mechanical HVAC systems whereas openable or removable components could be used in natural ventilation schemes. A tension or pneumatic supported fabric roof structure could in theory, be used to provide winter shelter and could be removed or withdrawn during warmer months to provide a service free outdoor courtyard. Such a scheme would, however, require the atrium walls to be weatherproof.

1.10 Transportation

The atrium is most often the natural and main circulation area and as such has some unique opportunities for vertical transportation. Since atrium elevators do not normally require a fire protected shaft, glass wall climber elevators may be used. Transportation systems for low rise buildings, such as atrium buildings, as opposed to high rise tower blocks of a similar floor area, offer possible advantages of

i) the use of escalators with high traffic handling capabilities and relatively low floor area requirements
ii) the use of lower speed (less costly) elevators
iii) the use of hydraulic elevators (up to maximum of 5 floor possible).

1.11 Economics of Atrium Buildings

In identifying possible economies of atrium building construction, it is important to acknowledge those benefits coming from a change of building form, typically from a high rise to a low rise, and those specifically associated with the inclusion of an atrium.

.1 Economics of Compact Construction

Compact design solutions as opposed to towers are often considered economical in the sense that they are generally cheaper to build than tower equivalents, primarily because of

i) their simpler structure
ii) reduced elevatoring
iii) less exposed skin area per unit of floor area
iv) potentially less excavation cost for providing underground parking space
v) more efficient use of floor space, i.e., higher ratio of net rentable to gross building area, than tower block, primarily because of reduced floor space for elevators, stairs, washrooms and service shafts.

Large deep plan areas are, however, difficult to divide up successfully to service small tenants and often deprive a significant percentage of the building occupants with the amenity of a window. Often significant amounts of money needs to be spent on "landscaping" interior office space to make it visual interesting. Glare from windows when viewed from the interior of such deep plan spaces is an acknowledged problem with such designs and invariably requires that artificial lighting levels be raised beyond those required for acceptable visibility in order to balance the brightness of the windows. Placing an atrium in the middle of a deep plan building can potentially overcome these problems providing more office space with a view window and useful daylight contribution.

.2 Adding an Atrium

Adding an atrium to a building is commonly considered to enhance the desirability of the building from a tenants point of view. This is attributed to the fact that the atrium can provide a very pleasant amenity space, permits more offices with windows and for those windows facing into the atrium itself, provides an interior view to the atrium which may be far more pleasant than the exterior view. This last point might be especially relevant in some urban environments and during the late fall to early spring periods.

For the developer, a more attractive building should lease quicker, and offices with window can generally be rented for higher amount than those without.

There are, however, many cost features, some involving additional costs, while others offering some economies that can be associated with atriums. A number of these as raised in the literature reviewed, are presented below.

.2.1 Potential Cost Premiums.

Additional cost may be incurred for:

i) complete sprinkling
ii) smoke ventilation systems
iii) stair pressurisation
iv) hose reels
v) upgrading of fire detection and alarm systems.

.2.2 Potential Cost Benefits.

i) use of non-weatherproof curtain walls between the main occupied space and the atrium.

ii) omitting the wall between the main occupied space and the atrium altogether. This may, however, pose some security problems.

iii) use of the atrium as a return air plenum thereby minimising the cost of return air ductwork and reducing fanning costs.

iv) use of the atrium as a space for ductwork supplying air to the offices thereby eliminating the need for a ceiling distribution and ceiling plenum space in the main occupied space.

v) the cost of landscaping and maintaining the atrium space may be less than the cost of exterior landscaping.

.3 Operating Cost Implications

A number of atrium design issues have been proposed as offering potential benefits to greater efficiencies. These include:

i) the use of an unconditioned or partially conditioned atria to serve as a buffer zone to the external environment.

ii) the use of the atrium to collect and store solar energy which may be useful for preheating ventilation air or otherwise providing heating for the principal building.

iii) the benefit of glare-free daylighting to spaces overlooking the atrium.

iv) the reduction of direct gain and cooling load to the atrium facing spaces by virtue of self-shading.

Issues such as these will be highly dependent on building location and the specifics of the building and its environmental control systems. Sections 2 and 4 discuss such issues in the context of a Canadian climate.

1.12 Planting

.1 Temperatures

Planting will most likely consist of subtropical and tropical (as opposed to temperate) plant material and environmental conditions should be planned to satisfy their requirements if the atrium is to include plants. Apparently there has been little success with using temperate plant material because of the difficulty of ensuring continuous winter cold periods during the plants' dormant period.

Environmental requirements will vary from plant to plant. However, most plants welcome changes of environment which duplicate their natural environment; for most cases a daytime temperature range of between 21 and 26°C and a nighttime range of 15 to 18°C is desirable.

Avoid exposing plant material to hot or cold drafts or cold radiation, i.e. site supply grills away from planters, do not plant near entrances, where cold draughts can be expected.

.2 Humidity

While most plants prefer high humidities, most will tolerate low. The provision of very high humidities is inconsistent with maintaining thermal comfort in the space.

.3 Lighting

Non-flowering plants should receive a minimum of 500 lux for a 12-hour period. 700 to 2000 lux is, however, preferable. Flowering plants typically require much higher levels.

Lighting should be even (symmetrical) and preferably from above to ensure uniform growth. Where this is not possible and, where uneven growth would be unattractive, consideration should be given to providing a facility to rotate large plants and trees.

Lighting should be turned off during the evening hours to duplicate natural diurnal changes.

Artificial lighting sources should be selected on the basis of promoting good colour appearance and supplementing daylight (where required) for plant growth. Sources should duplicate as closely as possible natural daylight. Ultraviolet (UV) and infrared (IR) sources and other "single" wavelength sources should not be used; however, it is not considered particularly worthwhile to use special "horticultural" light sources.

Sodium sources tend to make leaves look black, whilst mercury tends to make them look blue - mixing the two sources can be beneficial. Tungsten lighting is generally not recommended. Metal halide is preferred source being a wider spectrum source giving good colour appearance.

1.13 Building Code Implications

Except as otherwise noted, the following discussion is based on the 1980 National Building Code of Canada (NBC). Further, it is not the intent to reproduce the requirements as detailed in the building code merely to highlight those "additional" or special features required in buildings containing atriums.

Atrium buildings as such are not specifically addressed as a unique category of building type in the NBC - rather they are covered in two principal areas, i.e.

a) as covered malls separating buildings
b) as buildings containing interconnected floor spaces.

Each category has rather different requirements.

.1 Covered Malls

Covered malls have been a fairly popular feature in recent years, principally in mercantile building and can be considered as an atrium building. It is in this area, as opposed to atriums in hotels and offices, that most design experience has been developed and code requirements better established.

For this classification, buildings on either side of a covered mall are considered as separate buildings in which case the mall must be not less than nine meters wide. Other limits placed on the structure are:

i) mall to be used only as a pedestrian thoroughfare and those pedestrian-oriented activities not considered to constitute a hazard.

ii) mall to be sprinklered.

iii) mall to have a standpipe and hose reel system where the abutting buildings are not sprinklered.

iv) walls adjoining mall and abutting building to be one-hour fire rated and have limits placed upon the area of unprotected openings or the abutting buildings are sprinklered and smoke detection provided to shut down HVAC systems where such systems service more than a single major occupancy.

v) mall to have no direct access to more than one storey where the mall is below ground or to not more than two stories if above ground.

vi) fire alarmsystem in mall to satisfy the requirements of the abutting building.

vii) no more than one mall to be located above another mall, and in these areas, two-hour fire separation to be provided.

viii) generally non-combustible roof-ceiling assembly required.

The requirements under the mall classification are generally not as severe as those required under the interconnected floor spaces classification, although the mall classification does limit the use of the space to pedestrian activities and its geometries to no higher than two levels and not less than 9 meters wide.

.2 Buildings with Interconnected Floor Spaces

These are essentially multi-storey building in which floor assemblies that are normally required to be fire separations are pierced by large, non-closable openings.

Buildings containing such spaces are required:

i) to have (emergency) exits, opening into the interconnected floor space, protected by fire-rated, pressurised vestibules and provided with hose reels.

ii) to be generally of fireproof construction with a limit of combustible contents of 16 g/m^3 of interconnected floor space in those areas where the ceiling height exceeds five meters.

iii) not to exceed maximum height restrictions as detailed in the code.

iv) to be sprinklered and have water flow alarm to transfer signal to fire department.

v) openings at each floor level to have draft stops and close-spaced sprinklers (with cross baffles to prevent adjacent sprinkler head wetting) and smoke detectors.

vi) Mechanical exhaust, for smoke ventilation, located "at the top of the interconnected floor space" providing 6 Ac/hr (this figure is to be relaxed to 4 Ac/hr in the next NBC).

For this and other code purposes all floor area which is pierced by the non-closable opening, of which an atrium would be a prime example, is considered to be part of the "interconnected floor area" even when, say an atrium and adjoining occupied area is provided with a fire-rated separation.

The NBC relaxes the above provisions

i) where the interconnected floor space consists of the ground plus the storey either immediately above or below it and
ii) where openings are used only for walkways or escalators and
iii) where in some group A occupancies (assembly buildings), group D (business and personal service occupancies) and group E (retailing) occupancies.
iv) where the maximum floor area requirements, as laid down in the code, are not exceeded.

The Ontario Building Code allows further relaxations for these occupancies where the building is completely sprinklered and is limited to a ground level plus either the floor immediately above or below it.

Some or all of the requirements for atrium buildings as detailed in the codes may, in fact, be required in alternative design strategies and differences between an atrium and a non-atrium building should strictly be made on a building by building basis. Broadly speaking, however, atrium buildings, because of their lack of fire separations will, in most instances, require fire detection, protection and fire fighting and smoke ventilation schemes in excess of the requirements of conventionally fire compartmented non-atrium buildings with the possible exceptions of requirements for tall buildings.

.3 Miscellaneous Code Implications

Other code requirements that could impact on atrium design include:

i) For tents and air-supported structures. Sections in the code are oriented to separate tent structures as opposed to tent areas forming part of a permanent structure. As such limits are placed on a minimum separation from other buildings, plus requirements for the use of non-flammable materials and for open interiors without walls mezzanines or intermediate floors.

In addition, air-supported structures are required to have a standby blower to ensure continued support should one blower fail; are restricted in their use to exclude B, C and FI occupancies and classrooms; are not allowed above the first storey; and are required to have independently supported lighting and other equipment.

ii) For skylights. The use of combustible material for skylights is permitted but restricted to:

a) no more than 9 m^2 for any skylight with a maximum dimension of 3 m.

b) 2.5 m minimum spacing.

c) maximum area not greater than 10% of the floor area.

d) specific flame spread rating as detailed in the code.

1.14 Other Design Issues

Other issues, not specifically addressed in the previous sections include:

.1 Land Use Efficiency - atrium solutions can be applied to difficult sites otherwise difficult to build upon by

i) providing an internal view for those sites with an unpleasant environment (in terms of view, noise, etc.)
ii) providing a means of linking main occupied spaces or other buildings on awkwardly shaped sites.

.2 Low built form can minimise wind and shading problems on the local environment.

.3 Atriums can provide pedestrian routes and community areas within and between buildings making shopping and walking in extreme climates possible and pleasurable and possibly reducing use of automobiles in downtown core areas.

.4 Acoustic planning and security problems are obviously design issues to be concerned with, especially in atriums providing more than just pedestrian activities. Problems do not appear to be specifically addressed in the literature reviewed.

.5 City zoning laws may impact design of atrium from building with regards to maximum heights, maximum land coverage, set-backs, etc.

ATRIUM BUILDING ENERGY ISSUES EXPLORED

.1 Introduction

The following chapter explores in greater detail some of the design issues raised in Chapter 1. The text has been developed from a more detailed report (Reference 2).

In many ways the integration of an atrium into a building can be thought of as a compromise or blended solution to the two basic extremes of building form, i.e. the deep plan, compact form and narrow plan, envelope dominated. The option to build either compact or extended is of course, in the first instance limited by the actual gross (floor area) size of the building and is relevant primarily to large buildings.

Deep plan buildings have low envelope to floor area ratios offering potentially less heating and cooling demands in most climates than narrow plan buildings. A consequence of this low envelope to floor area ratio is, however, that less of the floor area can be usefully served by a window. In offices for example the concept of 'Burolandschaft' (open planning) attempted to maintain an open plan environment giving occupants in the deep plan at least some view of a window. In practice it was found difficult to strike an acceptable visual balance between the brightness of the window and the illuminance of the artificially lit interior workspace. To counteract this there was a trend to smaller windows, light reflecting glazing and higher artificial lighting levels. Also in most instances the diminishment of the view reduced the amenity value of the window. In addition, perimeter space was often partitioned off for senior executives or tenants paying high rents which often resulted in windowless office space being formed in the interior.

Conversely, narrow plan buildings offer the amenity of a window to a larger percentage of the occupants, as well as offering potential benefits of natural lighting and ventilation and useful winter solar gains.

Ignoring for the moment those constraints imposed by space planning and site restrictions, building narrow plan buildings could be pursued as either small floor plan high rise, or long thin floor plan low rise, i.e. a high rise "turned on its side". As an alternative to building long thin buildings, which would generally be considered as impractical for large buildings, the building could be broken down into smaller units or into 'U' or 'L' shaped buildings or into buildings with a central courtyard. Such a form of building means that the different parts of the building(s) will impact upon others, primarily by affecting the amount of sunlight and daylight seen by the various building parts and to a lesser extent by affecting wind driven infiltration.

Traditionally such building forms have been used to provide some degree of climatic control to an amenity space within or immediately adjacent to the buildings and in more recent times these 'open spaces' themselves have been enclosed by glazing into what we have commonly come to call atriums.

In analysing atrium design from an energy standpoint, it is useful to understand the impact of the basic building form on its own energy consumption before turning to considerations of an enclosed atrium space.

.2 Building Form

As a first approximation, one can equate potential energy efficiency to exposed skin areas. A better approximation results if envelope UA values are used instead of envelope area. The relative effects are demonstrated in Fig. 2.1; each building encloses the same overall floor area but have significantly different skin areas and UA values.

These simple approximations break down, however, where solar gains or daylight, play a significant part in the buildings energy flows. For instance, Figure 2.2 shows that theoretically, for a building making good use of solar energy, greater envelope to floor area does not necessarily mean greater per unit area consumption, i.e. the most energy efficient form is not the most compact (Ref.1). The actual optimum floor depth will vary from case to case and will depend on the complex interaction of outside climate, insulation levels, fenestration, lighting levels and controls, shading devices and HVAC systems.

In a similar but more complex manner, there are a number interactions taking place to affect the energy use of complex geometry buildings such as the main building space surrounding an atrium.

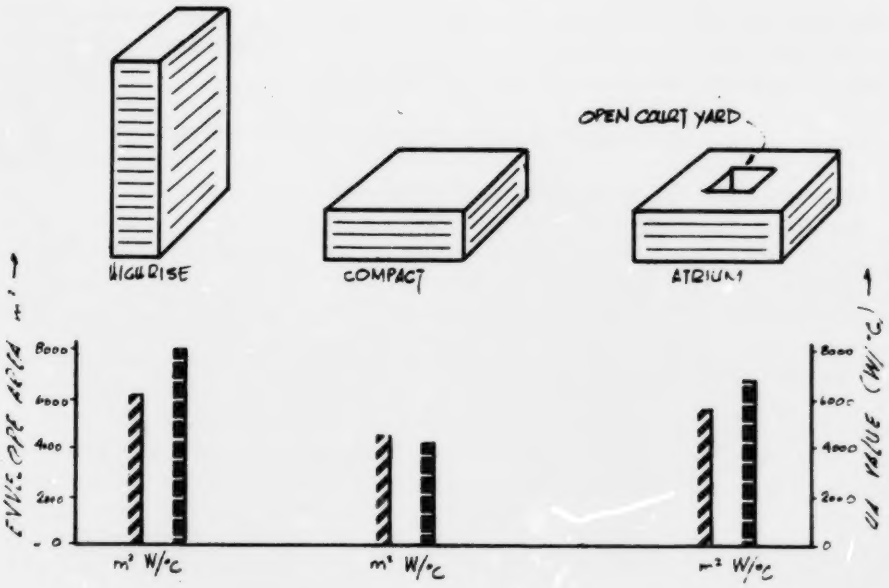


FIGURE 2.1
ENVELOPE AREA & UA
VALUES FOR BUILDINGS
ENCLOSING THE SAME
FLOOR AREA

▨ ENVELOPE AREA
■ ENVELOPE UA

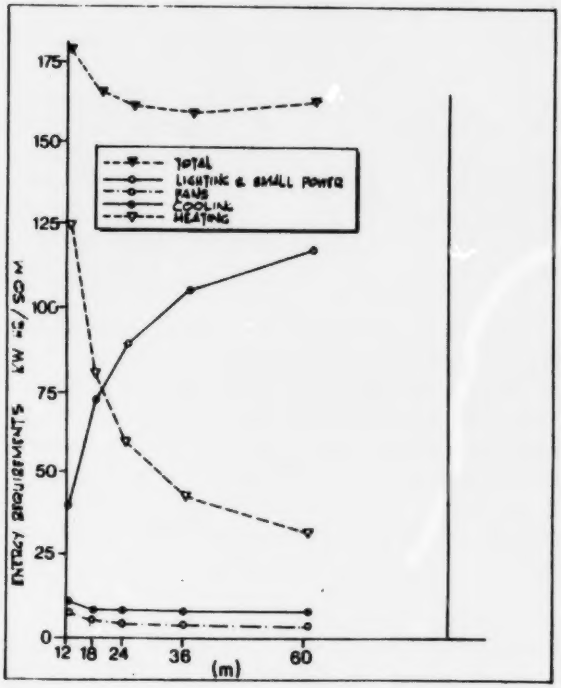


FIGURE 2.2
VARIATIONS OF ENERGY USE
FOR A NORTH-SOUTH ORIENTATED
OFFICE BUILDING. Figure
illustrates the variation in
energy for a "building" with
fixed envelope losses. (E&W
walls not modelled.)

The parameters that one might expect to influence energy consumption in an atrium building, over and above those influencing consumption in a simple square or rectangular building are:

i) Shape, e.g. centre courtyard, U-shaped or L-shaped

ii) Dimensions - as they relate to the self-shading of building facades

iii) Dimensions of the self-shaded portions of the building in relation to the total building areas

iv) orientation

Figures 2.3 and 2.4 summarise the results of a number of computer analysis aimed at exploring the effect of changes to the above variables. For all the analyses utilisation of daylight is assumed.

THESE ANALYSES AND ALL SUBSEQUENT EXAMPLES COVERED IN THE FOLLOWING TEXT ARE BASED ON A BUILDING LOCATED IN OTTAWA.

THE RESULTS ARE FOR THE CASE WHERE THE ATRIUM IS UNENCLOSED, I.E. FOR AN ATRIUM SHAPED BUILDING WITHOUT THE ATRIUM.

As one might expect where daylighting strategies are being employed, the effect of self shading on a space is to increase energy consumption and Figure 2.3 illustrates this point - energy use progressively increasing as one moves from the top to lower floors. One also sees that because self shading is obviously not as extensive in the U-shaped atrium as in the courtyard type, the effective variation in energy floor to floor is not as pronounced. These effects are best observed in the top row of bar graphs illustrating the consumption of the atrium facing zones. One can also notice the effect of building shape with the U-shaped building format offering a lower energy use. Even so the energy variations are not extensive, of the order of 10% at most.

When one considers the impact of form on the overall building consumption, i.e. not just the atrium-facing zones, as given by the lower set of bar graphs in Figure 2.3 , variations in consumption are only of the order of 1 to 2%. This reduction of impact is primarily due to the fact that the atrium-facing zones only constitute between 20 and 30% of the total space floor area. Variations in the ratios of perimeter to floor area and the varying percentages of southerly exposure are responsible for further weakening the impact of building shape and size on energy consumption.

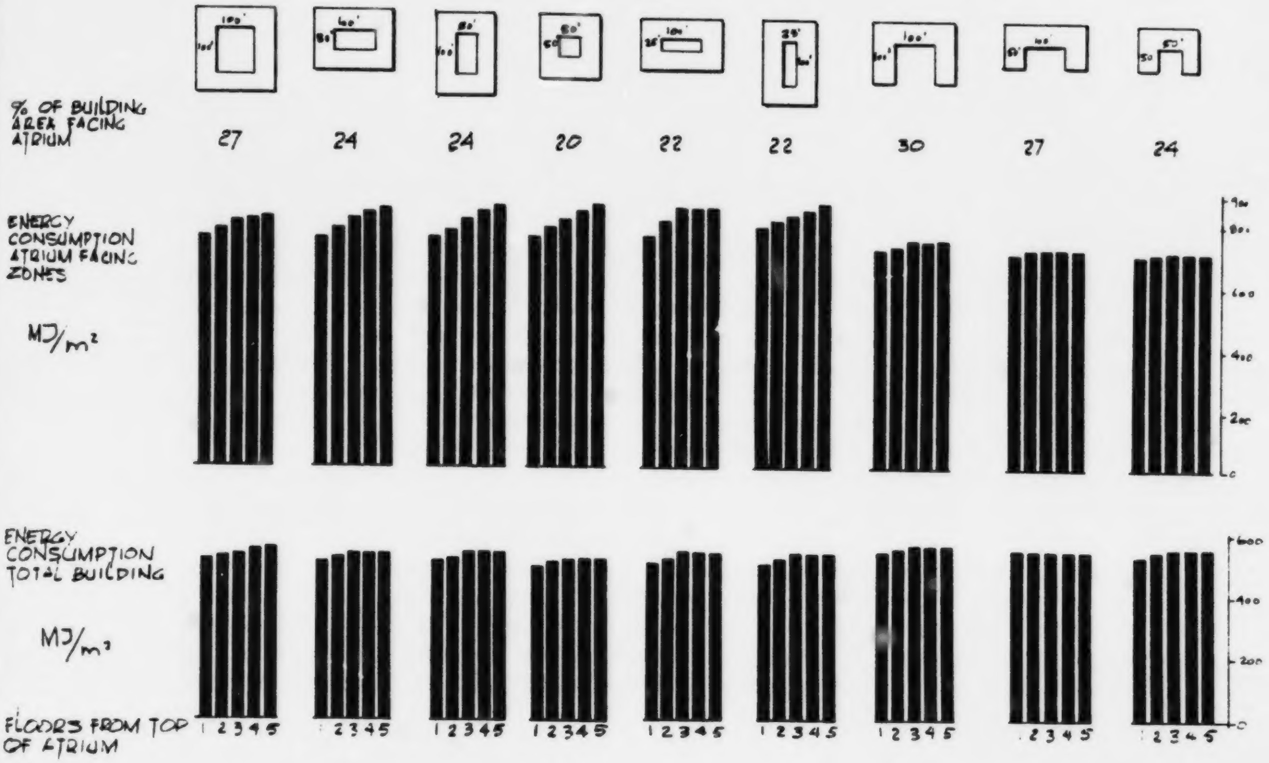


FIGURE 2.3
VARIATION OF ENERGY CONSUMPTION FOR ATRIUM FACING ZONES AND FOR THE TOTAL BUILDING FOR A RANGE OF UNENCLOSED ATRIUM BUILDING GEOMETRIES

The reader should note however that the results presented in figure 2.3 are based on computer simulations in which that atrium was modelled as unenclosed. As a result, and since the atrium-facing walls are more extensively glazed than are the exterior walls (the atrium-facing walls were fully glazed), the areas facing into the atrium consume proportionately more energy. The effect of enclosing and maintaining the atrium space at the same temperature as the main space would be to favour the atrium forms with most atrium facing perimeter, (e.g. the 100' by 100' four-sided atrium form) since heat loss would be significantly reduced in these buildings. One must, however, in such cases have to balance the reduced consumption of the main building with increased consumption of the atrium space. These tradeoffs are addressed later.

In contrast to its influence on energy consumption, the building form and orientation does have a strong impact on the amount of daylight and glare received by areas facing into the atrium. Understandably the areas facing into the atrium that receive the greatest amount of daylight are in those building forms in which the atrium provides the least obstruction of the sky. However, the designer is faced with making tradeoffs since these same building forms have the greatest problem with daylight glare. These relationships are illustrated in Figure 2.4. Orientation also has some influence on glare, for example there are fewer hours in which the glare index exceeds 22 when the 100 ft. x 25 ft. atrium is oriented with the longer axis running east/west as compared to north/south. It is therefore desirable to minimise the east/west exposure in a building as far as glare is concerned. Fortunately a building oriented in this direction (axis running east-west) has the greatest solar potential.

Where building self-shading is not considered adequate to minimise the adverse effects of glare, window shades may be added, however the most effective shades for reducing glare, tend to increase energy consumption because they reduce the potential benefits of daylight and free solar gains. The effects of such shading devices are shown in Figure 2.5.

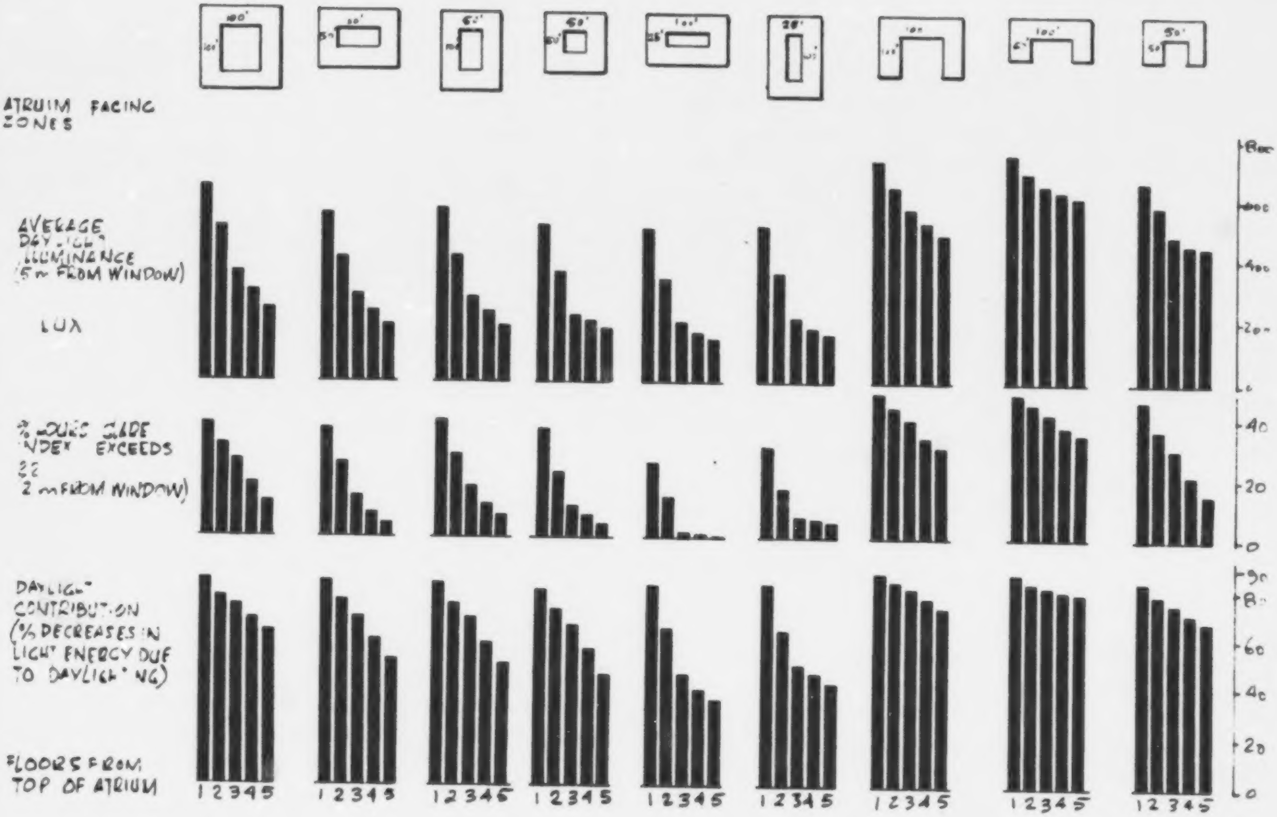


FIGURE 2.4
VARIATION OF DAYLIGHT CONTRIBUTION AND GLARE FOR THE ATRIUM FACING ZONES
FOR A RANGE OF UNENCLOSED ATRIUM BUILDING GEOMETRIES

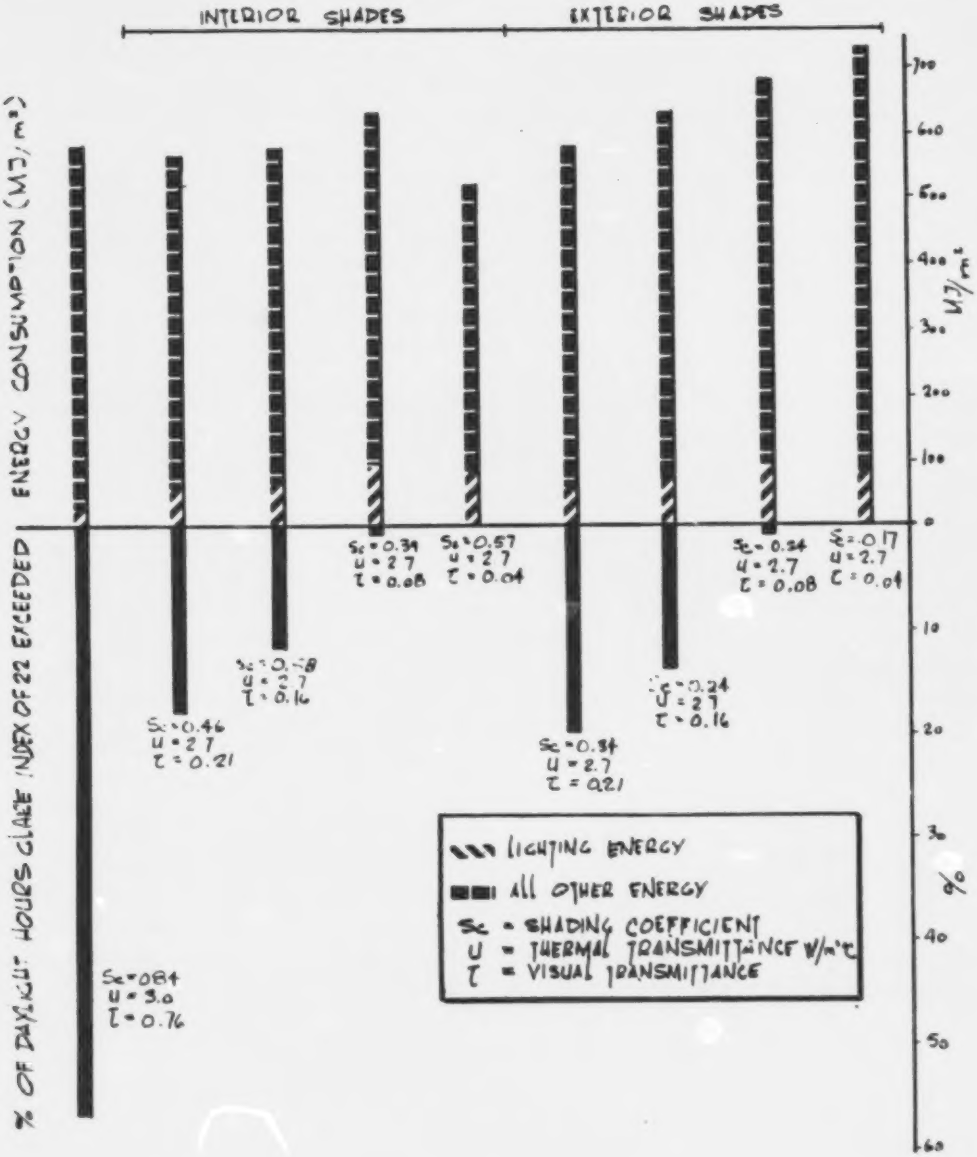


FIGURE 2.5
EFFECT OF SHADING DEVICES ADDED TO CONTROL GLARE IN
SOUTH FACING OFFICE SPACE

(Note different effects can be observed if the shades are controlled to optimise the use of energy, e.g. See Figure 2.7).

.3 Enclosing the Atrium Space

All the previous figures presented are for an 'atrium building' in which the atrium area is open. Enclosing the atrium will change the amount and pattern of energy use in the main building as well as creating energy needs for the atrium space itself where this area is to be heated.

Enclosing the atrium space impacts primarily in two areas, the first in affecting heat transfer across the walls now facing into an enclosed space, instead of exposed to outside conditions; the second in reducing the amount of solar radiation falling on these atrium facing walls. This change in solar radiation is caused by opaque elements added to the atrium enclosing structure and by the reflection and absorption of solar radiation by the atrium glazing - an effect which is constantly varying with the angle of incident solar radiation.

Enclosing the atrium space will inevitably result in a reduced building energy consumption if the atrium is left unconditioned, i.e. no heating, cooling or ventilation. Building energy consumption will rise progressively, from this lower level, depending on the degree to which the atrium is conditioned, as one trades off increased atrium consumption against reducing main building consumption. Some secondary effects are also at work when atrium conditioning is relaxed. For instance, better utilisation of solar gains can be achieved in winter if the space temperature is allowed to rise, under the influence of these gains, above the normal acceptable heating comfort range.

Despite increasing consumption from an unconditioned to a fully conditioned atrium, as Figure 2.6 illustrates, the consumption of a fully conditioned atrium building may in fact be less than if the atrium space were left unenclosed.

Obviously many factors will influence the atrium building energy use, such as the relative size of the atrium to the main building, and fenestration treatment and the example chosen may not necessarily be representative of all possibilities.

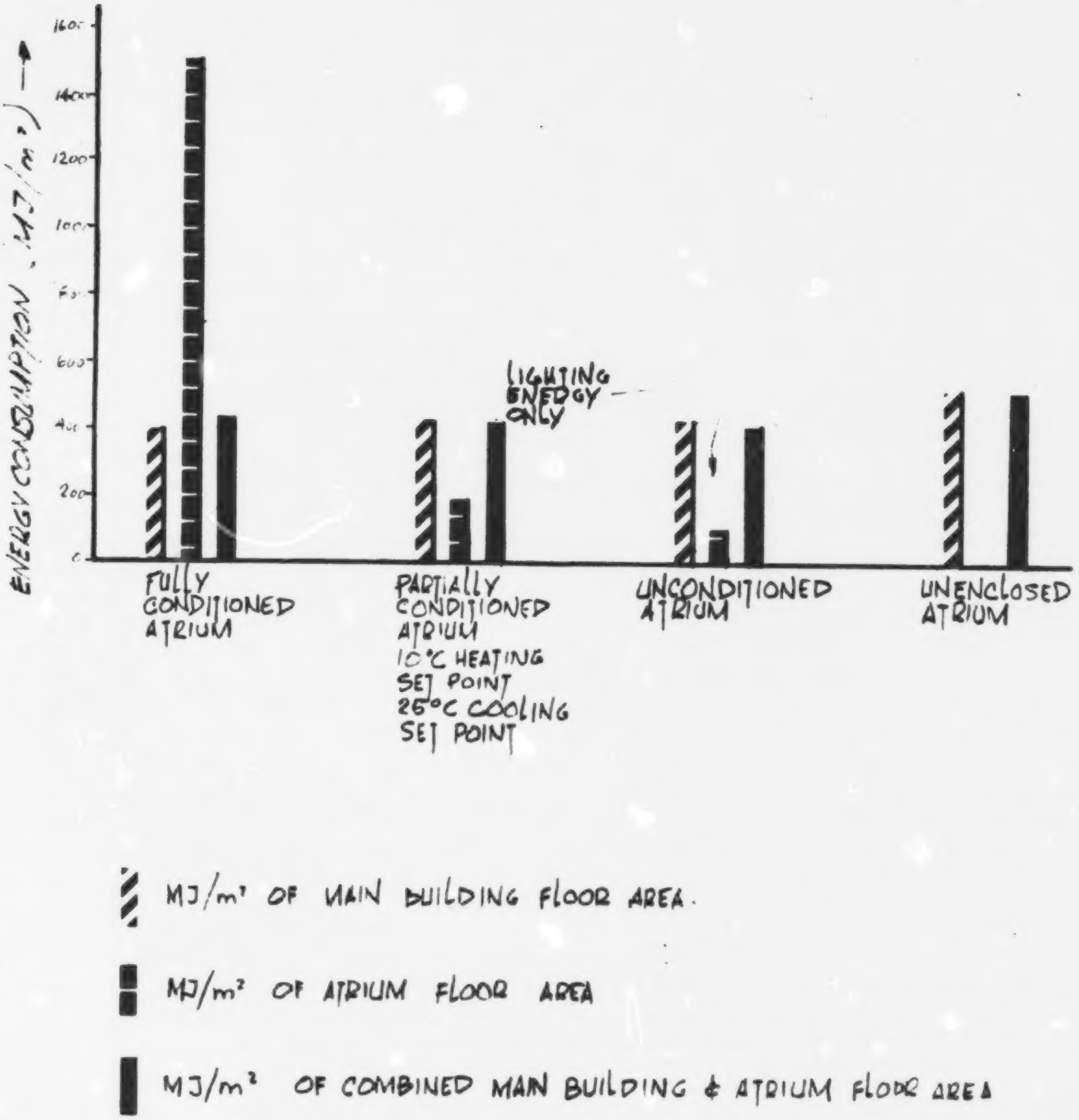


FIGURE 2.6
VARIATION OF ENERGY CONSUMPTION FOR A BUILDING WITH A FOUR-SIDED 50'X50' ATRIUM WITH VARIOUS ATRIUM CONDITIONING STRATEGIES

Another design issue that needs to be addressed when it comes to the decision to enclose an atrium is one of glazing. If the atrium is to be fully conditioned, it makes sense to provide the atrium with double glazing and, for economy of construction, to provide only single glass between the atrium and the main building (or no glass at all). If the atrium is not conditioned it makes more sense, energy-wise, that if only one glazing system is to be double glazed it should be the glazing between the atrium and the main building. Obviously somewhere in between none and complete conditioning there is a point at which the glazing strategy needs to be reversed. (Note that the results presented in Figure 2.6 were, for consistency, modelled with the double glazing always on the outside atrium wall.)

.4 Atrium Space Energy Issues

A number of analysis were pursued to investigate the effect on atrium energy use for a number of basic design issues which included atrium type, glass placement, solar shading devices, and natural and mechanical ventilation for cooling.

.4.1 Atrium Type and Glass Placement

Figure 2.6 summarises the results of a limited range of analysis exploring these issues.

The first conclusion that can be drawn from these results is that in isolation the three-sided atrium with an opaque well-insulated roof and vertical glazing appears to offer the lowest energy solution. This is based, however, on the assumption of a southerly exposed and a similar glass area to the four-sided atrium with horizontal glazing. For example, for the three sided atrium the energy use will be strongly influenced by its height, since the exposed area will vary with height, while for the four-sided atrium the exposed area will remain the same. Since it is assumed that a significant part of the solar entering through the atrium glass passes to the main building behind, and is hence not available to help heat the atrium space, increasing the size of the three-sided atrium beyond that considered in the example will increase its consumption beyond that of a larger four-sided atrium.

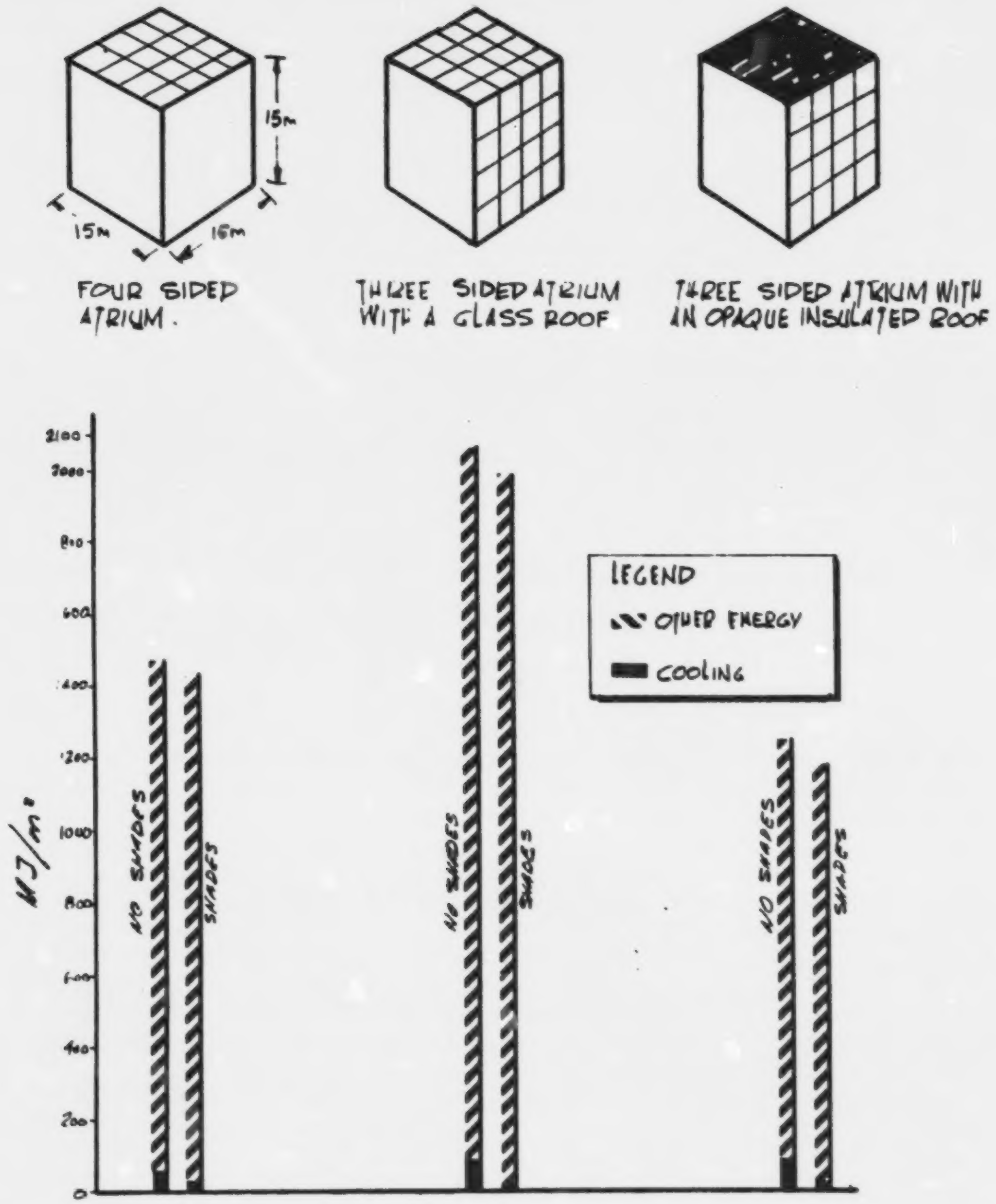


FIGURE 2.7
EFFECT OF ATRIUM TYPE, GLASS POSITION AND SHADING ON ATRIUM ENERGY CONSUMPTION

What is clearly to be avoided, however, if one does not wish to incur an energy penalty, is the use of both horizontal and vertical glass on the three-sided atrium; vertical south facing glass being the preferred solution.

One should not, however, jump to conclusions about adopting a three-sided atrium building configuration since for a complete picture one needs to consider the energy use of the total building. Although the previous section presented a three-sided configuration for lowest energy consumption with an unenclosed atrium (see Figure 2.3) this was for a specific case where the atrium facing zones were fully glazed, whereas the other facade were only 50% glazed, tending to discriminate against the form with most atrium facing perimeter, i.e. a four-sided atrium. Enclosing and conditioning the atrium could in turn tend to favour the four-sided approach and at least for one case as analysed (see Section 3) a four-sided solution resulted in a lower overall consumption rate than a similar, although not identical, three-sided solution.

.4.2 Solar Shading Devices

The use of solar shading devices on the atrium glazing in all cases lowers the energy consumption by reducing the atrium cooling load. Although the cooling load reduction is significant, up to 90%, the effect on total energy use is, however, rather small because of the small proportion of cooling required. To achieve these savings in practice it is necessary that the shading devices be operated such that they remain open as long as there is positive solar radiation and a demand for heat in the atrium and that they remain closed for as long as there is a demand for cooling. If the shades are left closed during the winter it is likely that the loss of useful solar energy will result in an increased energy use. The values presented in Figure 2.7 represent such a control system except that it was not possible to simulate the effect achieved by dropping shades during the evening hours to take advantage of a nominally improved U-value. Further, the results were derived specifically for external shading devices. Internal devices will generally give lower cooling energy savings.

Energy use in the atrium can be lowered even further if shades are applied to atrium facing zones, i.e. between the main space and the atrium, and raised when there is a cooling load in the atrium and lowered when there is a need for heating. Such a strategy relies on depriving the attached building of potentially useful solar gains in winter and passing on cooling loads to this space in summer and will inevitably result in a total building consumption higher than the case with shades on the atrium glass.

.4.3 Unconditoned and Ventilated Atriums

The statement has previously been made that the enclosing of an exterior atrium space will lower the energy use of the building if the atrium remains unconditioned (and even under certain circumstances if it is conditioned). What would be of interest to know, however, would be the conditions one could expect to have in the unconditioned atrium. For a particular example, specifically the building configuration used to produce the results in Figure 2.6, this line of questioning was pursued and the results are presented in the form of an atrium temperature frequency bin in Figure 2.8.

It can be seen that the temperature in winter never drops below 4°C (40°F) and for a limited amount of heating the atrium could be maintained above 10°C (50°F) which might be considered adequate for say a pedestrian route. High summertime temperatures are, however, present for a significant number of hours making some form of cooling desirable.

Figure 2.9 illustrates the effect of providing cooling by outside air both by virtue of a natural ventilation scheme and a mechanical ventilation scheme. The results presented are for 50'x50' four-sided atrium.

The mechanical ventilation scheme provides a constant 4 Ac/hr of outside air per hour while the natural ventilation rate varies with the difference between inside and outside air conditions. In this particular case the ventilation rate varied from no air charges when there was no wind and the atrium and outside air temperatures are the same, to 15 or more Ac/hr at high atrium temperatures.

The combination of mechanical ventilation in conjunction with a good solar shade would appear to provide acceptable control for the example considered. Obviously the results cannot be universally applied but are demonstrative of the potential for ventilation cooling. For the three-sided atrium case with vertical as opposed to horizontal glazing for instance, we could expect lower temperatures to be maintained since solar gains through vertical south glass in summer are lower than those through an equivalent area of horizontal glass.

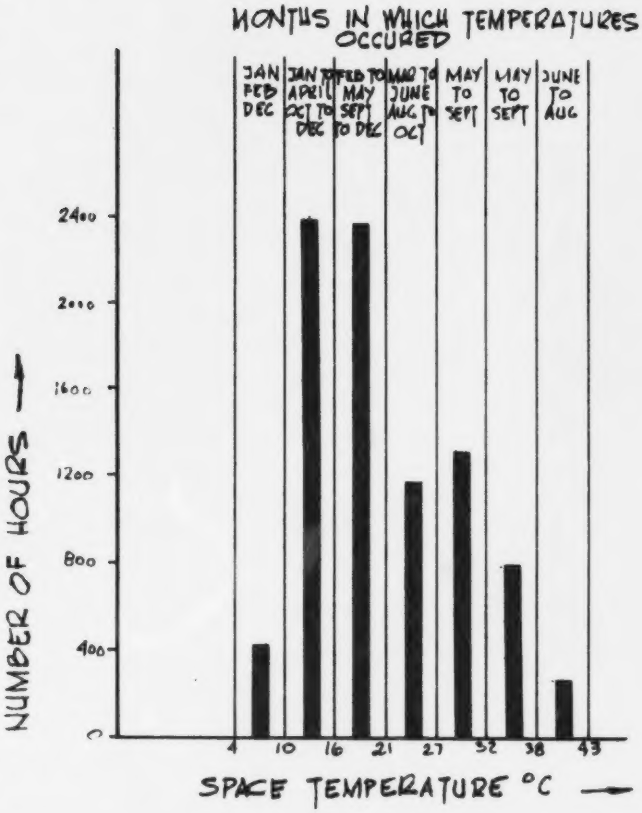


FIGURE 2.8
ATRIUM TEMPERATURE FREQUENCY BIN FOR A 50'X50', 4-SIDED
UNCONDITIONED ATRIUM

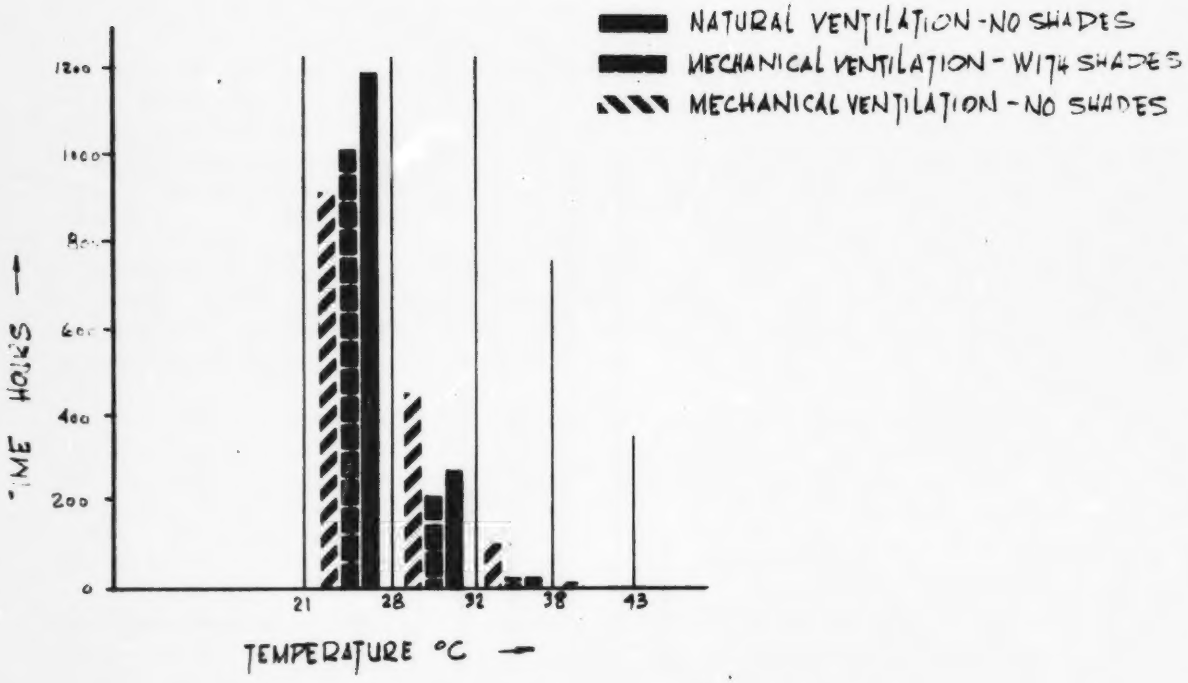


FIGURE 2.9
TEMPERATURE-FREQUENCY BIN FOR NATURAL AND FORCED VENTILATION COOLING FOR A 4-SIDED ATRIUM WITH AND WITHOUT SHADING DEVICES

In considering such ventilation schemes, the following additional points should be considered:

i) There is a potential heating penalty brought about by infiltration through the ventilation openings; care should be taken to specify very low leakage components. Stack effects developed in tall atrium spaces can be quite significant.

ii) Sub-cooling of the atrium, say down to 15°C (60°F), should be considered during cooler evening hours where possible to provide some stored cooling to help limit the following days temperatures. This was the strategy used for the numbers presented in Figure 2.9. This may, however, impact upon energy use for heating of the main building but if a temperature setback strategy is adopted in the main building, the effect should be minimal.

Cooling with outside air, although not as fully effective as using mechanical means, will reduce the consumption as compared with air conditioning unless very large fan powers are involved. Outside air cooling equipment is also potentially less costly than air conditioning equipment especially if the cooling can be done with the smoke extraction equipment. (A code requirement in Ontario requires four air changes per hour for smoke extraction.) Because the cooling energy is normally fairly low compared with heating requirement, the overall savings will however be relatively modest and part of these savings will be passed on to increase the cooling energy of the main building.

3. CASE STUDIES

3.1 Introduction

The intent of the case studies reported here is not to provide a definitive statement on the relative cost of atrium versus non atrium buildings, but to provide further example case studies that will hopefully enrich previous studies (References 1810, 1850 and 3340) by providing examples of different size, type and location, and perhaps by exploring issues not covered in previous work.

The conclusions and figures presented in the chapter cannot be taken and applied arbitrarily to other buildings of significant different designs. Rather it is hoped that the discussion on the principal factors contributing to the overall cost of the various building variations will provide a framework on which specific cost and design studies might be based and that the actual figures developed might be applied as appropriate to give some preliminary focus to design direction.

3.2 The Case Study Buildings

The basic intention of the case study was to investigate the relative cost between three basic building forms, "high rise" tower, compact, and atrium. Four office buildings were looked at, a ten-storey tower, a four-storey compact building, a four-storey four-sided atrium building and a five-storey three-sided atrium building. Floor layouts are given in Figure 3.1.

All the buildings were configured to have nominally the same net area of around 8,400 square metres. The net area being taken as the gross building area less service spaces such as elevators and elevator lobbies, washrooms, staircases, duct space and the atrium space itself. In the case of the tower and atrium configuration, the floor plan areas were developed on the basis of providing naturally lit office accommodation with a maximum depth from the window being set at 6.75 metres. This resulted in what might be considered a somewhat more slender tower than has been the common practice to build in recent years but for the purposes of this study allows us to compare office spaces with a similar visual environment. For the case of the compact building it is obvious that daylight cannot be provided to the central areas and in this respect this building form does not provide a similar type of office accommodation as do the other forms. The inclusion in the cost study does, however, provide a basis of comparison since in most cases compact form building is potentially the cheapest to build.

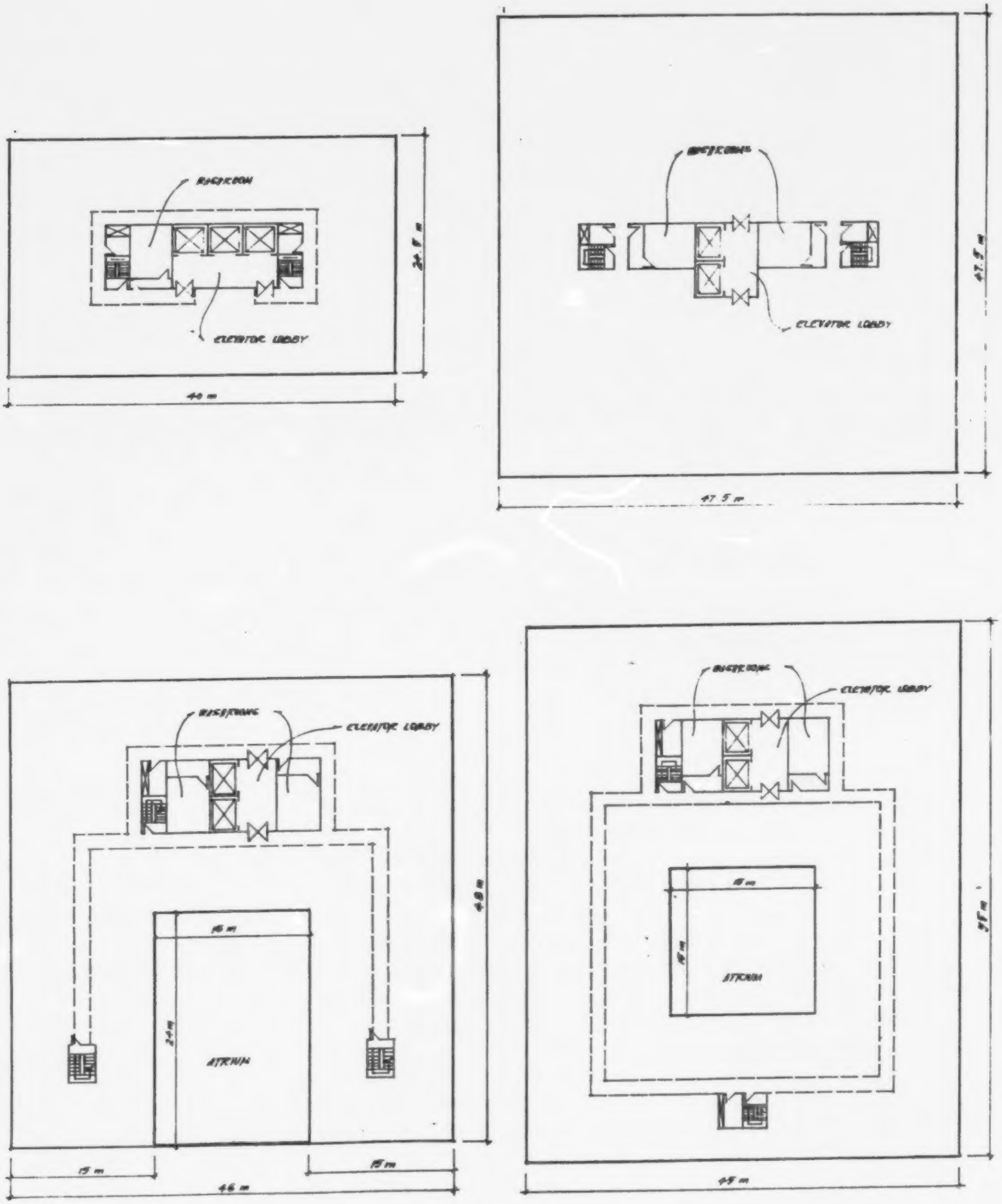

RESTROOM
ELEVATOR LOBBY
24.5 m
40 m
RESTROOMS
ELEVATOR LOBBY
47.5 m
47.5 m
RESTROOMS
ELEVATOR LOBBY
16 m
24 m
ATRIUM
48 m
15 m
15 m
46 m
RESTROOMS
ELEVATOR LOBBY
18 m
18 m
ATRIUM
38 m
45 m

FIGURE 3.1
FLOOR PLANS FOR THE FOUR CASE STUDY BUILDINGS

The four buildings all of which have clear double glazing and an automatic daylight controlled lighting system, were analysed in two basic forms, first with clear double glazing without shading devices and second with shading devices. The shading devices used were automatically operated, internal roller shade type.

A summary of other pertinent data concerning the buildings is given in Table 3.1.

In addition, the effect of replacing mechanical cooling in the atrium with a mechanical ventilation system was explored.

3.3 Annual Energy Consumption Comparisons

Annual energy consumptions and annual energy costs are shown in Figure 3.2.

The compact form building offers the lowest energy consumption and annual costs. This estimate is based on the assumption that all building forms have the same installed lighting level. Unless the perimeter office areas of the compact form building are partitioned from the view of the interior office spaces, this lighting level may not be visually acceptable and higher lighting levels throughout the building would be required.

Considering the three building forms with similar office accommodation, i.e. all offices with windows; the four-sided atrium offers the lowest energy solution while the three-sided is the highest consumer.

The addition of shades has a marginal effect on the overall energy consumption. In three of the four cases there is a net increase in consumption while in the fourth case there is a net decrease. Because of limitations of the analysis method used, it would be wise to assume that this trend could in fact be reversed. The reason for the increase results in the fact that there is a loss of daylighting contribution when the blinds are dropped which is not offset by the cooling load reduction. In theory at least this could be changed by different types of shading devices, outside shades for instance, with better cooling load reduction performance, or a different control philosophy.

The addition of shades does, however, have a more dramatic effect on the maximum cooling load, and hence plant size, with peak loads reductions ranging from 11 to 28%.

Substituting mechanical ventilation for air conditioning in the atrium space has little effect on the overall building energy consumption.

WALLS:
Curtain wall, with insulated spandrel panels,
U-Value = $0.40 W/m^{2\circ}C$

ROOF:
Inverted, four-ply asphalt, U-Value = $.28 w/m^{2\circ}C$

WINDOWS:
Exterior Office - Double Clear Glass, 50% (of interior view wall) less 10% for mullions
Atrium Facing Office - Tempered Single Clear Glass, 100% (of interior view wall) less 10% for mullions and barrier rail
Atrium - Double Clear Glass - 100% (of interior view wall) less 20% for mullions

LIGHTING:
Office 500 lux, $20.7 W/m^2$ Electrical Load, continuously dimmable system
Atrium - $10.8 W/m^2$ electrical load, on with occupancy

EQUIPMENT LOAD:
Office - $2 W/m^2$

HVAC:
Atrium
A/C, Single Zone, constant volume, variable temperature.
economiser cycle. $20^\circ C$ heating, $25.5^\circ C$ cooling.
Ventilation only - 4 Ac/hr.

Office
AC, VAV, economiser cycle, minimum ventilation rate of
27 l/s per 100 m^2 off floor area, $20^\circ C$ heating,
$25.5^\circ C$ cooling.

Chiller - Seasonal COP of 4.5

Boiler - Seasonal efficiency of 72.5%

SUBSTRUCTURE:
Conventional Column bases and strip footings, no basement

STRUCTURE:
Concrete flat slab with columnms on a 6 metre grid

TABLE 3.1
SUMMARY OF PERTINENT DATA FOR THE CASE STUDY BUILDINGS

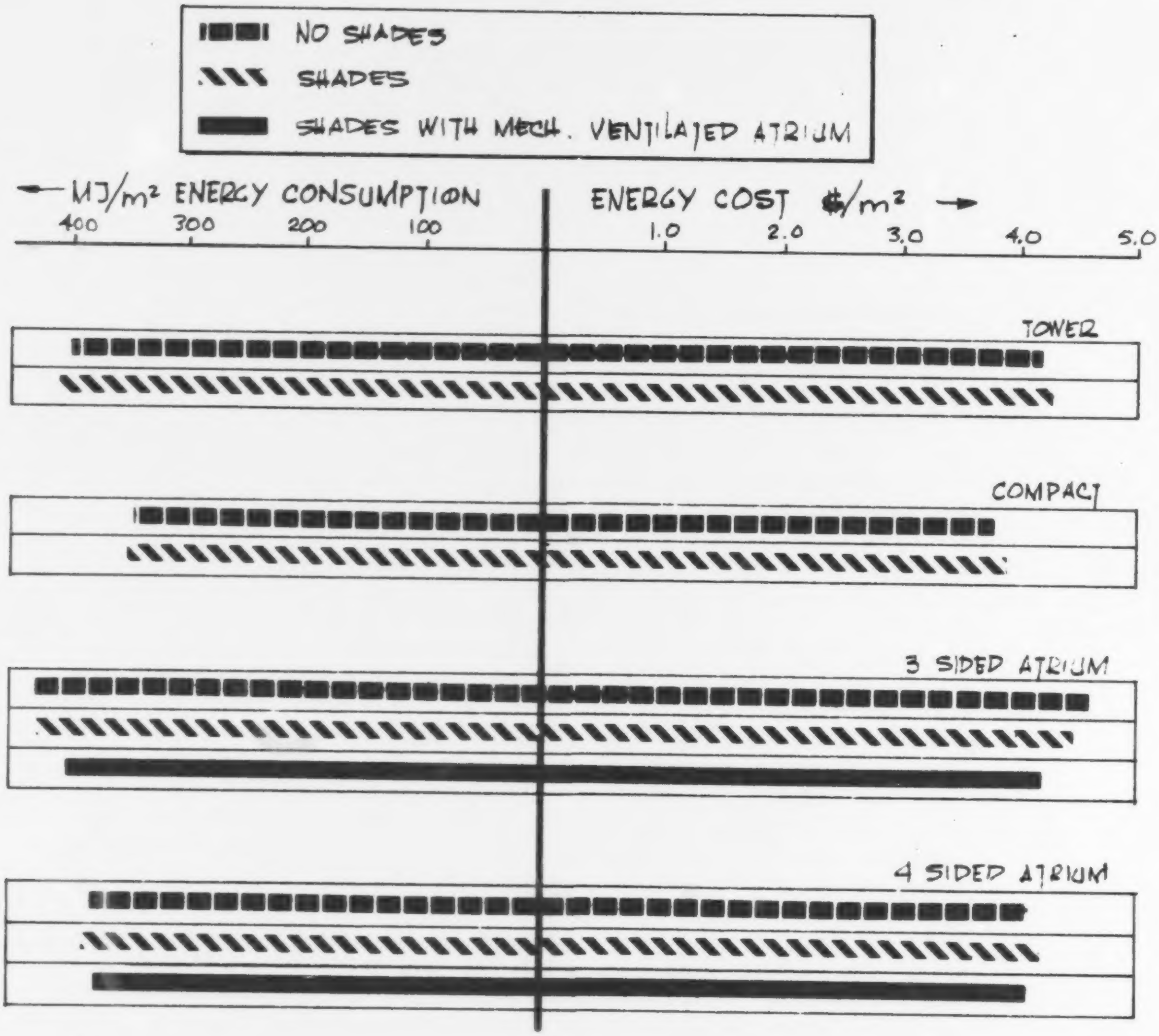


FIGURE 3.2
COMPARISON OF ANNUAL ENERGY CONSUMPTIONS AND ENERGY COSTS

All values are normalised to the net office floor space

3.4 Principal Factors Contributing to Cost Variations

.1 Principal factors contributing to capital cost differences between the various building forms are presented below. In most cases where numerical data is provided it is likely very specific to the building models developed for this cost study and given the possiblity of different building sizes and configurations different cases may give very different trends. The important point for the designer is to recognise the potential areas of difference.

.2 Net to Gross Area

Net to gross areas differ between the case study buildings from a low of 86% for the tower to 92 to 93% for the other buildings. Buildings with higher net to gross should tend to lower per unit costs of net rentable space.

For the atrium buildings the actual atrium space is not included in the above figures, nor in the net areas expressed throughout this section, and representes an additional amenity space that the non-atrium buildings do not have.

.3 Envelope

Inevitably with different building geometries, envelope areas will vary and for the case of the atrium buildings there will be added cost associated with the main building-atrium partition. Further there will be differences in per unit cost of the atrium and main building cladding that is assuming that the atrium is more extensively glazed than the main building. The relative areas and costs for the four case study buildings are shown in Figure 3.3 and as can be expected, generally the greatest envelope cost occur in those buildings with largest envelope area. In these case studies the unit area cost of the wall cladding is approximately 30% higher than the roof finish and glazing is 10% higher than the walls. It therefore follows that the tower building, which has the greatest wall area and the three-sided atrium building which has the greatest amount of glazing, have the highest envelope costs.

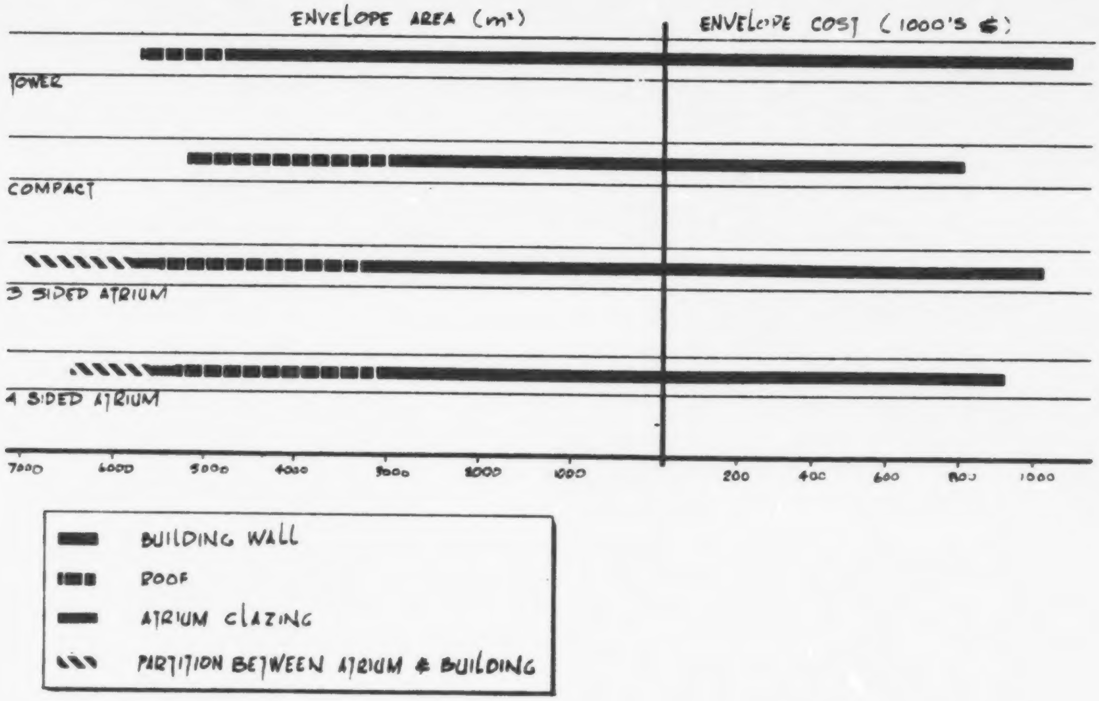


FIGURE 3.3
COMPARISON OF ENVELOPE AREAS AND COSTS

.4 Atrium Size

Primarily as a consequence of trying to provide naturally lit space it is inevitable that the atrium for the 3-sided atrium building has to be larger than for the four-sided atrium solution. In our case the four-sided atrium is 225 square metres in floor area with a four-storey building while the three-sided is 384 square metres within a five storey building. There are of course many other possible solutions.

The difference in atrium size will influence envelope costs and these differences for the case study buildings have been included in Figure 3.3.

.5 Ground Floor Leasable Space

A consistent storey height of 3.65 metres for above the second floor was chosen with a 4.87 metre ground storey height. This is fairly normal practice to allow retail and prestige space on the ground floor. It does result, however, in the lower rise buildings providing a higher percentage of 4.87 m high space than does the tower. The additional envelope costs have been included in Figure 3.3, however no attempt has been made to separate ground floor rentable space from the remaining space on the basis that such space may have a higher leasable value than higher level space.

.6 Parking

The case study buildings are all assumed to start at grade.

In practise, however, it is likely that parking facilities would be provided and consideration should be given to the increased cost of deep excavation under a tower building to provide similar parking areas to the low rise solutions, or the increased structural and waterproofing costs should the excavation extend beyond the footprint of the building.

Conversely for similar sized sites, there would be more room for surface parking should this be permitted, with the tower solution.

.7 Site Development and Landscaping

Given the same size of site, site development cost would be higher for the tower since there would be more site left to develop than for the low rise.

For the purposes of this study and as opposed to assuming some site area, an incremental site development cost has been included based on the difference in the footprint areas of the various buildings. Against this figure, for the case of the atrium buildings, are interior landscaping costs. No allowance has been made for 'landscaping' inside the deep plan compact office building.

.8 Open and Unwalled Atrium

A full glass partition is assumed between the atrium and the ajoining space. Omitting the partition wall has an obvious direct cost benefit which may or may not be partly or completely offset by other considerations such as noise transmission, fire safety, security and HVAC system differences. No attempt has been made within this study to analyse the cost implications of such a design decision.

.9 Elevators

Costs are based on geared traction elevators operating at the same speed for all cases. It is suggested however that potential cost savings through the utilisation of hydraulic elevators for the low rise be pursued.

.10 HVAC System Capacity

Premiums are incurred for the tower and atrium buildings for larger peak design loads.

Comparisons of peak demands are given in Figure 3.4.

.11 Construction Times

Shorter construction times can be expected for the lower rise buildings and for the case study construction times have been estimated at 42 weeks for the tower, 38 for the atrium buildings and 30 for the compact. Further, there is considered some potential for early occupancy in the atrium buildings.

Shorter construction times mean lower general contractors overhead and the opportunity for a quicker turnaround of cash flow.

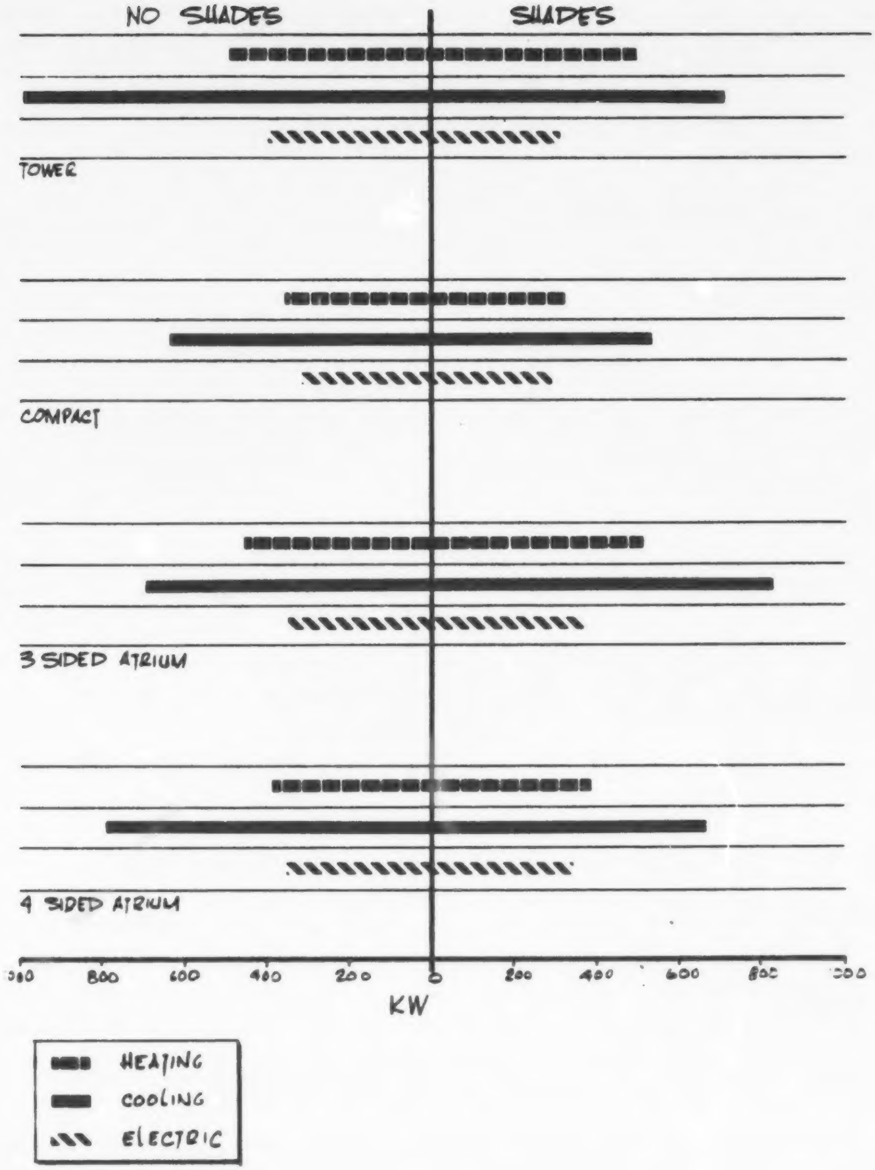


FIGURE 3.4
COMPARISON OF PEAK LOADS (kW)

* Coincident peak load includes cooling, fans, lights

.12 Fire Safety Systems

Hose reel and sprinkler systems have been included for all buildings. Sprinkler systems are not, however, specifically required in the compact and 10 storey tower, although they would be in larger or taller structures, but have been included since building of such a size are considered difficult to lease without them.

Additional costs are incurred for the atrium buildings for stair vestibule pressurisation, close spaced perimeter sprinklers and smoke detectors in the atrium, and for smoke ventilation equipment in both the atrium and tower buildings. Additional costs are also incurred for fire pumps in the 10 storey tower and 5 storey (three-sided) atrium building and for a fire elevator in the 10 storey tower. Due to the emergency facilities required to remain operational, generators of increasing capacities are required in the four-sided atrium building (50kW), three-sided atrium building (100kW) and tower building (150kW). A generator is not required, although it may well be desirable, in the compact building.

The atrium and tower buildings have emergency voice and communication fire alarm system while the compact has a standard audible alarm system only.

.13 Miscellaneous

A pumped cold water system is assumed for the 5-storey and tower building. Actual site conditions would determine whether the pumps would be required for the 5 or even 4 storey building.

3.5 Life Cycle Cost Comparisons

.1 Introduction

Life cycle costs are compared on the basis of present dollar values (PD's) using the criteria given in Table 3.2

Present Dollar Values are the values of the future expenditures expressed in current $ values after adjusting for inflation and the time value of money.

Capital costs are presented on the basis of March '85 (Ottawa) figures. Differences in capital cost have been discussed in the previous section.

Energy cost comparisons have been covered earlier (Section 3.3).

Maintenance costs are generally based on historical data and records.

.2 Comparison of Building Forms

Both capital and life cycle cost are clearly the lowest for the compact form building with the tower and three sided atrium building being similar and highest. The four-sided atrium building lying somewhere inbetween.

While the compact building has the lowest cost it does not necessarily follow that it is the best investment value since the annual rental value of the atrium building will likely be higher than that of the compact form because of the additional amenity space offered by the atrium and since all office space has a view window and access to natural light - be it to outside directly or through the atrium.

.3 Economics of Shading Systems

Viewed from the perspective of total cost window shading systems add little percentage-wise to either the capital or life cycle costs. In absolute terms, however, shading devices do add appreciably to the cost. Contributing to the costs are the increased energy cost and maintenance cost estimated on the basis of motor replacement once every 5 years and 5 year cleaning cost of $1 per square metre. The figures should, however, be viewed in the light that some form of window shading is inevitably required by clients and is desirable at times of the year to minimise discomfort resulting from direct solar radiation. On this basis the incremental cost of providing automatically controlled blind with good solar shielding properties over and above a regular blind is probably well worthwhile. Such an argument is reinforced since, as previously

Time Period	20 years
Average Annual Inflation	6%
Nominal Discount Rate	10%
Nominal Rate of Interest	4%
Labour and Materials Escalation	6% per annum
Electrical Energy Escalation	7%
Natural Gas Escalation	8%
Current Electricity Cost	4.8 cents/kwH
Current Gas Cost	2.9 cents/kwH

TABLE 3.2
SUMMARY OF ECONOMIC CRITERIA

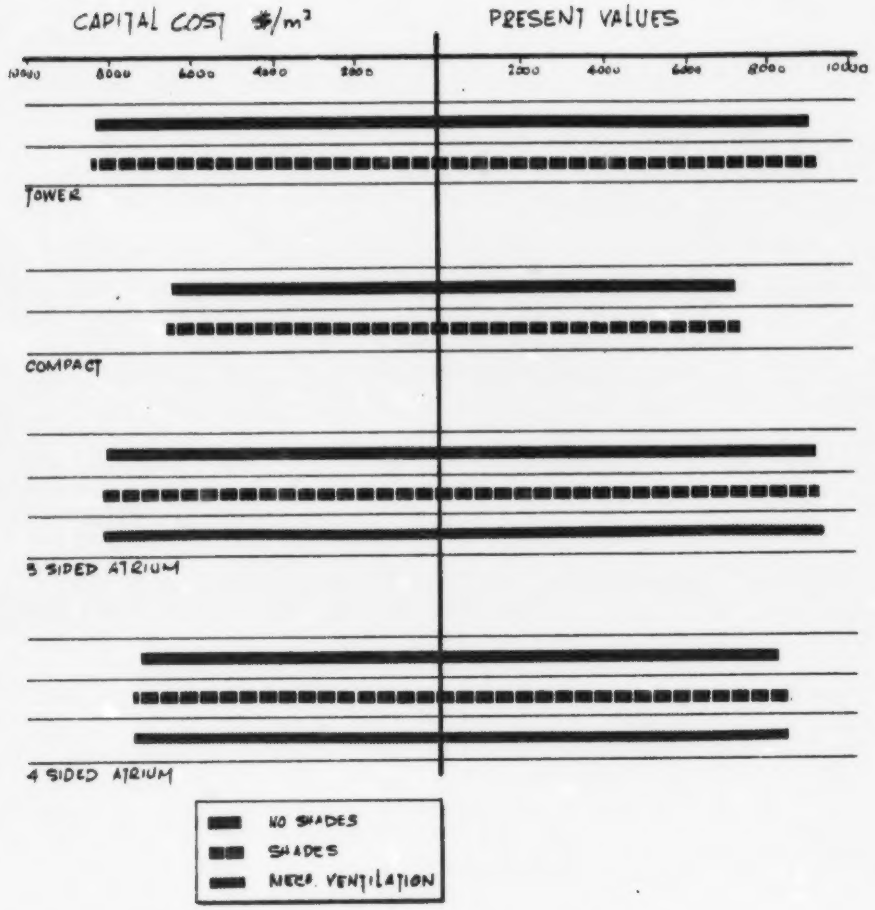


FIGURE 3.5

COMPARISON OF CAPITAL AND LIFE CYCLE COSTS

Note: i) All figures are in $1000's.

ii) Buildings have similar net office floor areas.

iii) Atrium buildings have an additional amenity floor space over and above the floor space provided by the non atrium buildings, i.e. for 3-sided atrium 384 m^2 and for the 4 sided atrium, 225m^2.

discussed, solar shading used in conjuction with daylight controlled lighting increases energy when blind useage precludes daylight contribution. To allow blind useage at times of the year other than when it is absolutely necessary will compromise any economic advantage that a daylighting system might have offered.

For cases where daylighting systems are not provided different factors must be considered.

.4 Economics of a Mechanical Ventilation System for Cooling

Because it is affecting only a small portion of the overall building and energy use the elimination of air conditioning in the atrium does not have a big impact on the overall cost. Mechanical ventilation does, however, offer a capital of life cycle cost benefit that is worth considering.

4. MODELLING TECHNIQUES

4.1 Introduction

Modelling of atriums and buildings containing atriums presents a particularly difficult challenge to the energy analyst. To our knowledge there is no program that can currently handle the wide range of possible design issues that the architect or engineer might wish to address.

Because of the complexity of the modelling problem, the development of 'inhouse' software for atrium modelling is not recommended. The analyst should look to ways of working with existing and emerging software and to select software that best covers the range of design issues for which there is most interest.

Existing software can be applied to the analysis of atrium buildings by either ignoring some of the building complexities, injecting some engineering judgment into the process, or by looking at ways of using the software to get the desired result, albeit if by some roundabout manner.

One can also treat atriums and atrium buildings in the same manner that we might look at conventional building spaces but such an approach obviously fails to make use of the atrium in a constructive,energy saving, or innovative manner.

Ignoring some of the complexities involved in a problem can, and often is applied quite acceptably to engineering problems, where the complexities are known to have only a small impact on the overall result; the difficulty of applying such a philosophy to atrium buildings is that there is a general lack of widespread atrium modelling experience that makes decisions on what is and what is not important somewhat arbitrary. A similar argument can be made about engineering judgment - energy models have been developed to assist and develop engineering judgment in the very complex area of building energy analysis and the use of such detailed models can be expected to precede, not follow, engineering judgment.

For our own modelling purposes we chose to work with the DOE program primarily because of our own familiarity with the software and our knowledge that it could probably satisfy a large number of our requirements. This is not to say that other software would not be as good or better than the DOE program or cover aspects that the DOE program could not address.

A great deal of experience was built up using the program for atrium building analysis which, as related on the following pages, should help the would-be atrium analyst; particularly in the use of the DOE program and generally in the selection and use of other software.

THE FOLLOWING DISCUSSION IS, HOWEVER, PRESENTED IN A MANNER WHICH IS IN PARTS SPECIFIC TO THE USE OF THE DOE2.1B PROGRAM.

4.2 The Modelling Problem

Perhaps the most basic problem making the modelling of the atrium buildings particularly difficult stems from the self-shading effects of the building geometry. This is particularly the case where one wants to consider solar radiation passing through the Atrium space into the adjoining space. While programs such as DOE have been developed to handle both attached and detached shading, software has generally not been developed with such complex geometries as three and four sided atriums in mind. In the case of the DOE program, attempts to simulate a four-sided atrium building as a single model i.e. with each zone comprising the model being alternatively a shading surface and a shaded surface not only proved to be complex, but also resulted in incorrect output.

To circumvent this problem, the building must be broken down into thermally independent zones for the purpose of the LOADS simulation, This, however, limits the possibility of modelling zone to zone heat transfer resulting from conduction or air movement. Such a limitation need only be of concern where the zones are to be at significantly different temperatures, for instance, if the atrium space is not to be conditioned.

If the effects of solar entering the space adjoining the atrium are considered to be unimportant then the building need not be described as geometrically 'correct' and the effect of self-shading can be ignored, in which case glazing between the atrium and the adjoining space would essentially become interior partitions. Such an approach, however, also precludes the simulation of daylighting in the adjoining space, but might be considered where atrium glazing, or glazing between the atrium and the main building is limited, where shading is installed to prevent penetration of solar into the main building, where the geometry of the atrium itself precludes any significant solar penetration (e.g. deep, narrow atrium spaces), or where daylighting strategies are not to be pursued.

If the analyst is primarily concerned with the overall annual energy consumption of the main building of an atrium design (i.e. excluding the atrium itself), then it is probably reasonable to ignore the effect of solar radiation passing through the atrium into the main building. This is particularly the case if the floor areas of the zone facing into the atrium represent less than 30% of the main building floor area. While the component energy breakdown (i.e. heating, cooling, fans, etc.) will not be as accurate with this method of modelling, it is expected that the estimated total energy consumption will be within 10% of the consumption calculated by the more complex method.

If, however, the analyst is interested in the component energy consumption, peak loads, daylight illuminance or glare in individual zones facing into the atrium, then it becomes necessary to model the distribution of solar energy. It is also necessary if the analyst is modelling the atrium itself and unless this is done heating energy will be underestimated and cooling will be overestimated.

Tips for modelling the flow and distribution of solar radiation in the atrium and adjoining building are described in the following section (4.3). Other atrium modelling techniques are described in subsequent sections which may be of interest for those looking at specific design options such as natural ventilation. Unless specifically described otherwise, all discussion is based on the simulation of thermally independent zones.

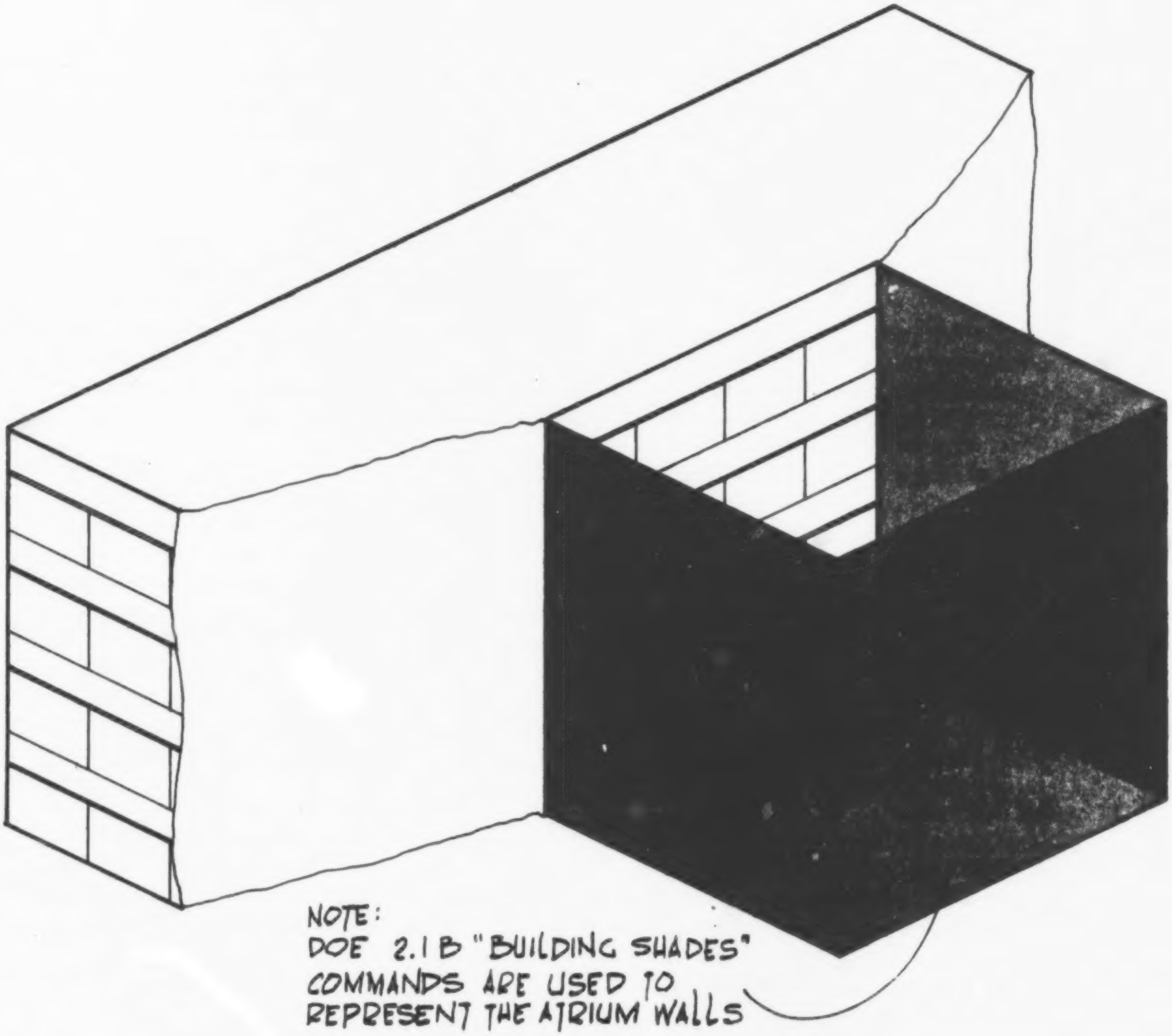
HVAC system options were generally not addressed in these studies. The adjoining buildings were modelled with Variable Air Volume systems and the atria were simulated with single zone constant volume systems.

4.3 Modelling Solar Radiation Flows

There are two main aspects to this problem. The first is concerned with the flow of radiation into the building adjoining the atrium space, the second is with the amount of radiation remaining in the atrium space itself.

.3.1 Solar Gains & Daylighting in the Atrium Adjoining Spaces

It is relatively easy to model a space facing into an unenclosed atrium by describing the surrounding atrium walls as "external shading" (see Fig. 4.1). As mentioned earlier, however, it is necessary for each orientation to be treated as an independent model.



NOTE:
DOE 2.1B "BUILDING SHADES"
COMMANDS ARE USED TO
REPRESENT THE ATRIUM WALLS

FIGURE 4.1
MODELLING SELF SHADING

Modelling a space facing into an enclosed atrium is however much more difficult since solar radiation passing into the adjoining space must first pass through the outer atrium glazing (see Fig. 4.2). In other words there are two distinct glass radiation-heat transfer processes involved:

i) At the outer Atrium glass where a certain amount of solar radiation is transmitted; conduction heat transfer being from the atrium space temperature to the outdoor ambient and

ii) At the atrium/adjoining space glass where a further reduced amount of radiation is transmitted to the adjoining space; conduction heat transfer being from the atrium to the adjoining space temperature or vice versa.

Since most programs, DOE included, can only model one of these processes at a time, it is necessary to try and accommodate the second in some other manner. The most simple solution to the solar gains problem is to consider the combined transmittance of the glazing layers but this is only reasonable if the glazing surfaces are parallel to one another. If this is not the case one must try and accommodate the effects of varying transmission rates with varying angle of incidence on the two non parallel glazing layers. One way of achieving this is to represent the transmission characteristics of one of the layers of glass by a "shading schedule" which characterises the hourly and seasonal transmission characteristics of the glass.

In our own work hourly schedules, one for each month, were used. The values in the schedule can be calculated for each "sun up" hour of twelve design days, representing an average day in each month. The design days should be selected such that the sun angles are representative for all days in the month and should be days on which there is little or no cloud cover.

For each design day hourly data is output from a DOE model which describes only the atrium glazing. The output consists of the solar energy incident and transmitted through each "window". From this data the fraction of the incident solar energy that is reflected off the atrium glass is calculated, i.e.

$$1 - \frac{\text{transmitted solar}}{\text{incident solar}}$$

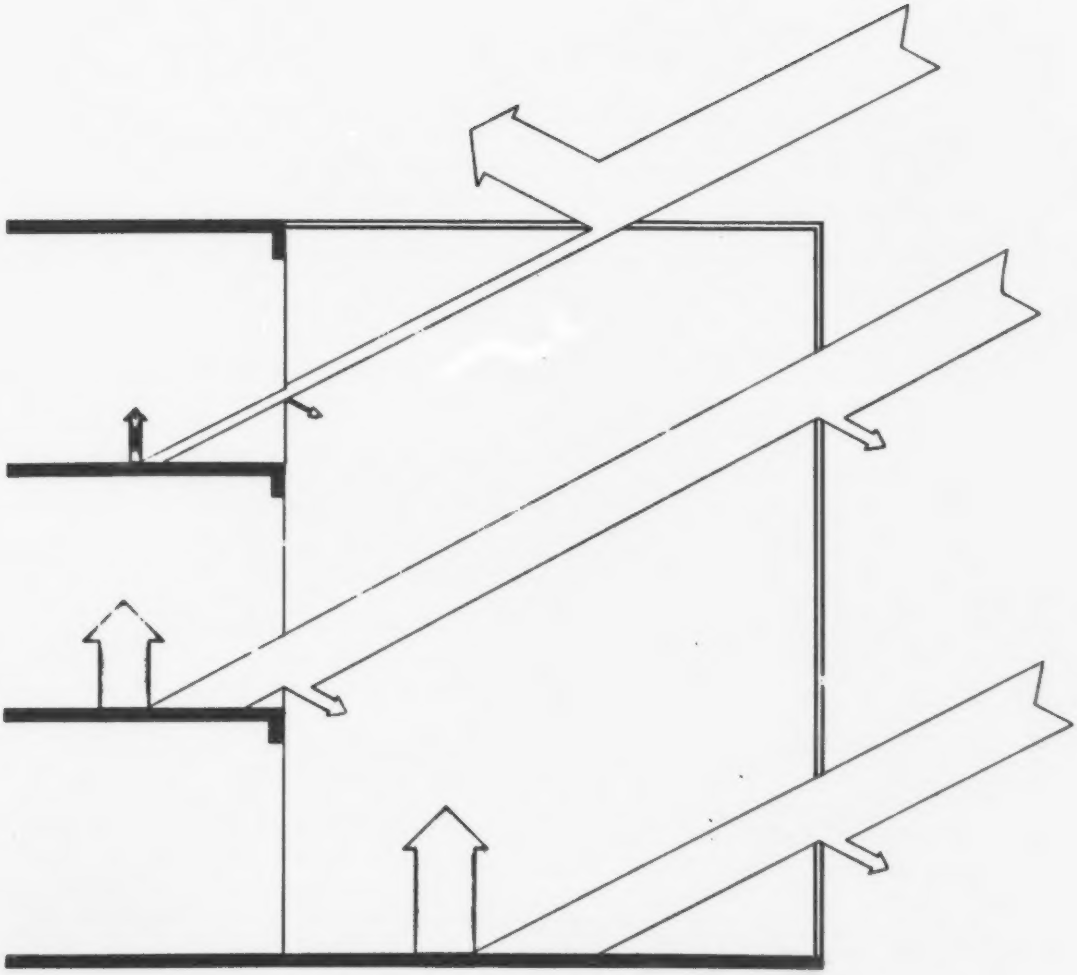


FIGURE 4.2
SOLAR RADIATION FLOWS THROUGH THE ATRIUM

Modelling the solar radiation entering into the adjoining space through an enclosed atrium can then be achieved by setting up a model in the same manner as one would for an unenclosed situation and applying the derived 'shading schedule' to the windows facing into the atrium. Because these windows are not exposed to outside temperatures, it is necessary to adjust the U-value of the glazing to keep the conductance heat transfer rate correct. Where the atrium and the adjoining space are at similar temperatures, the U-value should be set to a very low value to give very low (negligible) heat transfer rates. Avoid using zero (0), although this would be the correct value where the temperatures are identical, since zeros can often create unexpected compute errors.

The distribution of daylight is handled in a similar manner as the solar energy. The same schedule is referenced at each atrium-facing window as a "visible transmission" schedule and is used to reduce the amount of daylight each area receives accounting for the daylight reflected off the atrium glass.

Additional complications occur when one wishes to simulate the effects of movable or variable transmission shading devices since in DOE only one set of "shading schedules" can be accommodated at one time. One specific type of movable shading can, however, be modelled and this is an idealised form of optimum shading, which lowers the shades whenever there is a cooling load and raises them when there is a heating load. Such a system can be evaluated by running the model twice, first without shades and then with shades.

The heating energy consumption can then be taken from the no shades run and the cooling from the shaded run. In those spring and fall months when there is both a heating and cooling load, the electrical energy consumption (lights, fans, etc.) can be averaged between the two runs. Otherwise the electrical energy is taken from the no shades run during the winter months and with shades run during the summer.

.3.2 Solar Gains and Daylighting in the Atrium

The amount of solar energy staying in the atrium can be difficult to model since some solar will pass directly through to the adjoining building. The analyst can approximate the amount staying in the atrium using a method similar to that which was described in the previous section. In this case, however, models are first constructed for each of the zones adjoining the atrium in order to calculate the amount of solar leaving the atrium (which is equal to and given by the amount transmitted to adjoining space). The atrium for those models is assumed to be unenclosed.

Next a simple model of the atrium is run in order to determine the amount of solar energy incident upon the atrium glazing. The fraction of solar energy that is incident on the atrium glass, and stays in the atrium can then be calculated from the hourly output of the above models; i.e.

$$1 - \frac{\text{solar energy transmitted through all atrium-facing windows}}{\text{solar energy incident on the atrium glass}}$$

The fractions are used as the values in the "shading schedule" for incorporation into the atrium model. The atrium is set up as a normal single-zone model except that the above calculated shading-schedule is applied to the atrium glazing.

To model daylight levels in the atrium space it is not necessary to develop 'visible transmission' schedules, rather a weighted average reflectance can be specified for the walls to the adjoining space. The glass in these walls can be expected to have a reflectance in the range of 5 to 15%.

Movable shading devices may be approximated by the same method used in the previous section by modifying the window glass characteristics and running the model twice, once with and once without shades.

4.4 Thermal Zoning

As with all types of buildings, the question of splitting the building down into thermal zones for the purpose of simulation is one which deserves careful consideration. In atrium buildings the fact there are varying degrees of self shading on the atrium facing spaces tends to suggest a need for breaking the atrium facing spaces down into a large number of zones.

Such a route, however, can create an enormous amount of work for the analyst and increase the potential for error.

If the analyst is primarily concerned with overall building energy consumption it would be quite reasonable to simulate the atrium facing zones on the basis of one zone per floor per orientation. For those floors with limited solar view; e.g. floors deep in the atrium, north facing, small atriums or with minimal glazing, or where daylighting is not a consideration, some grouping of floors would be appropriate. An example of the sensitivity of energy use with zoning is illustrated in Figure 4.3 which may help put the discussion into context. It should be remembered also that the atrium facing zones only represent a fraction of the total floor area of the building and fraction of the total floor area of the building and that this fraction is inevitably less than 50% and usually a lot less, which means that the impact of inaccuracies in the modelling of these zones will be reduced in the context of the overall building consumption.

Conversely, if the analyst is interested in hourly load information, daylight or glare in individual rooms or sections of the atrium facing zones, then division into small zones is necessary. Again, Figure 4.3 could be of help to the analyst obtaining some feel for the possible level of zoning required.

4.5 Modelling when the Atrium & the Adjoining Building are at Different Conditions

Unless the effects of daylight and solar radiation entering the atrium adjoining spaces are not considered, heat exchange between the atrium and the adjoining space cannot be handled explicitly. There are, however, a number of ways in which such effects as omitting the atrium heating and cooling systems, can be approximated. A number of such techniques are described below.

.5.1 Unconditioned & Partially Conditioned Atriums

It is not possible to model the complete building in one simulation unless solar heat gains into the atrium facing zones are ignored. It is possible, however, to determine the impact that the surrounding space has on the energy consumption and temperatures of the atrium whilst accounting for the solar gains. Likewise it is possible to determine the incremental impact of an unconditioned and partially conditioned atrium on the main building consumption.

This can be achieved by simulating the atrium and main building as two adjoining thermal zones, one zone being the atrium which is set up in the manner previously described, the other zone representing the space surrounding the atrium. This second zone need only be descirbed as a conditioned space and could for instance be described as a simple interior space in order to minimise the amount of coding required. The conductance of the atrium-adjoining space partition walls need also be described in order to account for heat transfer between these two spaces.

If one wanted to access the impact of say having an unconditioned atrium, one would run the model twice, once with a fully conditioned atrium and again with the atrium unconditioned, from which the absolute energy consumption of the atrium and the incremental difference in energy consumption for the adjoining building could be obtained.

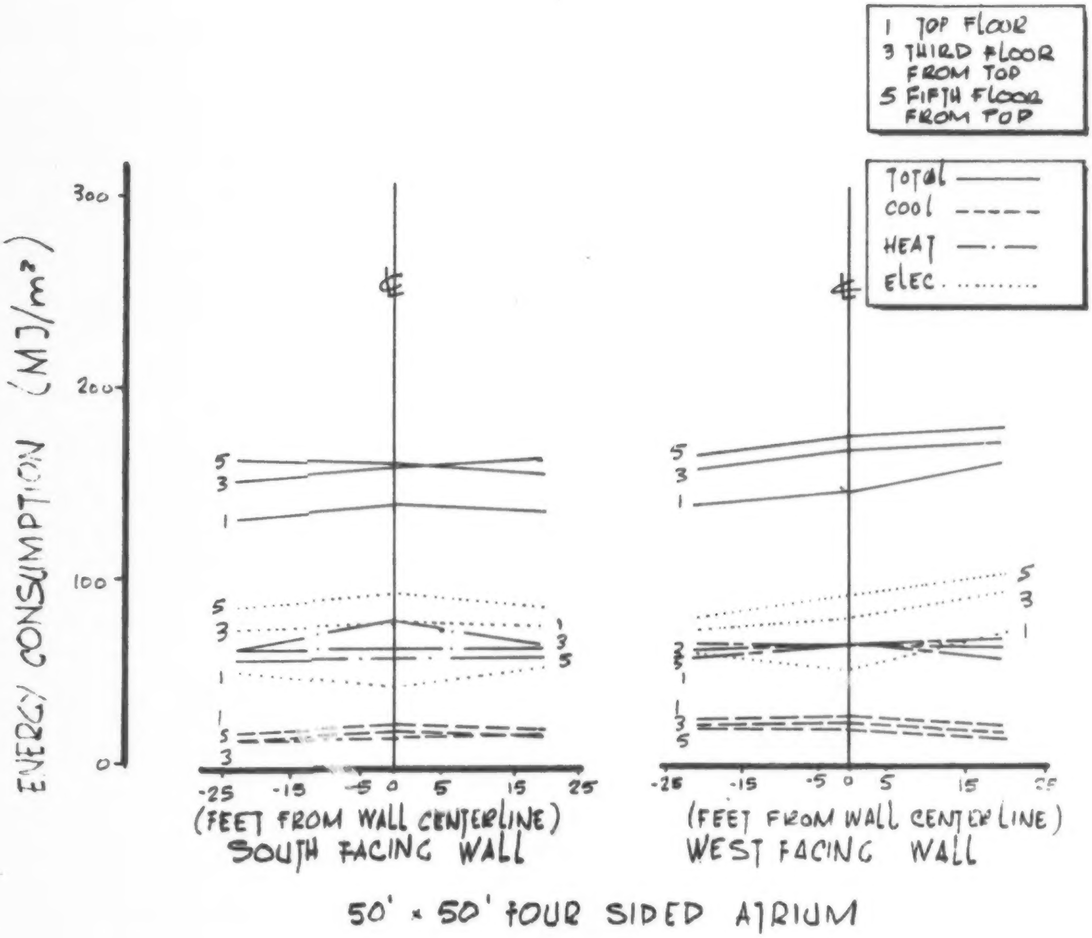


FIGURE 4.3
SENSITIVITY OF ENERGY PREDICTIONS TO ZONING

.5.2 Mechanical Ventilation

Since, arguably, temperature control in the atrium space could be relaxed somewhat from that desirable in continuously occupied spaces, there exists a possibility of minimising mechanical servicing costs by providing mechanical ventilation in place of air conditioning.

A desirable control strategy for such a ventilation cooling system would be to operate the fans whenever the space temperatures exceeds the desired space 'cooling' setpoint and when the outside air is two to three degrees lower than the inside temperature.

In addition, it might be considered desirable to subcool the atrium to, say 15°C, allowing the atrium to store cooling within its fabric to offset subsequent cooling demands.

DOE is not, however, able to model such a system directly. However, the capability of a mechanical ventilation system to limit atrium temperatures can be evaluated by running the atrium model, developed as previously described, with a fixed, continuous outdoor air supply rate and a "heating setpoint" the value of which represents the lowest acceptable internal temperature below which the ventilation would be shut off. A constant "air change" rate in the 'infiltration' command can be used to specify the outdoor air supply rate. Obviously such a system would not be installed and operated in this manner and the heating consumptions from the simulation will be quite meaningless; the model does, however, allow the evaluation of the ventilation cooling system by providing atrium space temperature data.

.5.3 Natural Ventilation

As an alternative to mechanical means a designer may wish to use natural ventilation. The design problem here lies with the sizing of the ventilation openings needed to provide acceptable internal temperatures. The process is essentially an iterative one and the designer must first chose a ventilation opening size and carry out an analysis using this information. The results of this first analysis can then be taken as an indication of whether larger vents are required or if smaller ones can be used.

Using DOE in such a process presents somewhat of a problem since the best available option for simulating natural ventilation in the program is to use the CRACK method option under the infiltration command. Although this method is sensitive to both wind and stack effects, it is not ideal for simulating natural ventilation because the infiltration flowrate is calculated in the "LOADS" part of DOE where the inside temperature is assumed to be constant. This prevents the simulation of stronger stack action due to rising atrium temperatures.

To circumvent this problem, the model can be run a number of times, each time with a different LOAD 'setpoint temperature'. For instance runs might be made with setpoint temperatures of 22, 26, 30 and 34°C. Hourly space temperature output from each of these runs can then be used to build up an interior space temperature bin profile by:

i) for the 34°C run, adding up the hours that the temperature is between 32 and 36°C

ii) for the 30°C run adding up the hours that this temperature is between 28 and 32°C

and so on for the remaining runs.

The method is not a rigorous solution since some hourly data tends to fall "between the cracks in the runs" but the method will however give the analyst a good idea on the atrium's potential performance.

A further complication arises when trying to use the method suggested above and that is that DOE uses an "infiltration coefficient" to characterise a uniformly distributed wall leakage opening as opposed to accepting an absolute size and location of leakage opening. To get around this problem an equivalent infiltration coefficient must be calculated that gives the same infiltration rate as the desired vent opening and location; the method given in Chapter 22 of the ASHRAE Book of Fundamentals can be used to calculate this.

Since a natural ventilation system would require some form of dampered opening to stop ventilation when it is not required, any evaluation of the potential benefit of natural ventilation should include analysis of the additional heating energy use likely to be created by damper leakage. This can be achieved by running a regular atrium model for the heating season with the leakage characteristics of the dampers characterised by a new equivalent infiltration coefficient.

5.6 Miscellaneous Modelling Problems

The following items are common problems that cannot be explicitly modelled using DOE. However, each can be approximated in order to assess the item's impact on energy consumption and comfort.

.6.1 Infiltration

Infiltration problems unique to atrium are created by the lack of horizontal partitioning which allows air to flow freely through the atrium space. This may also cause an increase in infiltration in the main building if the atrium partition wall is loosely constructed. Varying occupancy rates can further complicate the problem, especially if the atrium is used as a lobby directly connected to the outside conditions.

The effects of these problems can be approximated by using hand methods (such as ASHRAE or Shaw-Tamura NRC method) and daily occupancy patterns. These results can be incorporated into the DOE model using the "AIR-CHANGE" method and an infiltration schedule. Schedules can be used to adjust the infiltration on an hourly, daily and monthly basis.

.6.2 Temperature Stratification within the Atrium

DOE and to our knowledge all other building energy analysis programs, do not address thermal stratification. Since atriums are typically tall open spaces they are particularly prone to stratification. To complicate the problem, the designer may want to destratify in the winter and use the atrium as hot air reservoir in the summer.

Although the authors have not attempted to model thermal stratification using DOE, one approach might be to divide the atrium into several horizontal zones. The horizontal boundaries between each zone would be assigned a U-Value to approximate the transfer of heat due to the buoyancy effect of hot air. Characterising the boundary heat transfer by the specification of an equivalent U-value would, however, remain largely a matter of guesswork.

.6.3 Heat Loss to Grade

The energy consumed due to heat loss to grade of a large office building typically represents only a small percentage of the total energy consumption and can often be widely approximated or even ignored without significantly affecting the overall predictions.

However, if the analyst feels that the heat loss to grade warrants further investigation, then he might consider additional calculations external to the energy analysis program. For example, a detailed hand method such as those developed by Mitalas at NRC, may be used to estimate the average monthly heat loss for a particular basement/slab configuration. Assuming the appropriate U-Values and surface areas, an effective ground temperature can be calculated for each month and entered into the DOE input file.

More important than a slab's heat loss to grade is its daily interaction with solar gains and the surrounding air. DOE and many other energy analysis programs will model this interaction given the thermal characteristic of the slab, adjacent materials (such as carpets) and air film resistances.

.6.4 Effect of Snow Cover on Roof Lights

The need to model the effects of snow accumulation on a roof can be important, particularly with regards to the collection of snow near roof lights and the consequent reduction in solar and daylight transmission, and to a lesser extent its effect on heat transfer through the roof.

If the analyst assigns shading and visible transmission schedules to these windows he can approximate this effect. The analyst may also want to consider the increase in thermal resistance due to the snow. He may do so by using conductance schedules.

Snow collection against the vertical glass surfaces can be assumed to reduce the solar and daylight transmission by the ratio of the glass area covered by snow to that of the complete glass area. In past studies the authors have not made any allowance for the change in U value of the window due to snow cover on the basis of personal observations and supported by calculations of glass surface temperature at various outside ambients suggesting that snow piled against glazing tends to melt close to the surface of the glass.

Snow on the horizontal surface of the roof can be assumed to reduce the heat conduction and transmission of absorbed solar radiation. Since no direct facility to simulate this is available in DOE, the roof can be treated as a horizontal glass surface with a U value equal to that of the opaque roof and with a solar shading coefficient calculated to approximate the effect of absorbed solar radiation. Since shading and conductance scheduling of glazing is a facility provided in DOE it is possible to simulate a changing U value with snow cover and to set the absorbed solar radiation to zero when snow is on the roof (on the assumption that solar energy melts the snow and is not transmitted through the roof). An average value of 0.3 W/m^{o}C can be taken for the conductivity of snow.

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5.1 Introduction

A complete list of papers identified as dealing with the subject of, or related to Atria is given following this introduction.

Those papers that have been reviewed during the course of this work have been keyworded and are presented in Table 5.1 following the list of papers.

A description of the keywording used is provided under 5.3 near the end of this section.

Finally, a list of Publishing Bodies covering the range of publications referenced is given in Table 5.2 to aid location of reference material. For those readers experiencing difficulties obtaining specific papers, Leslie Jones and Associates have available all references appearing in Table 5.1

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5.3 Literature Keywording Description

MODELLING Paper deals with thermal, daylight, and/or energy modelling of atria and the adjoining spaces.

ENERGY Text discusses either the impact of design strategies on energy usage or discusses design strategies for minimising energy usage.

HVAC Text discusses heating, ventilating and air conditioning system design.

ELECTRIC LIGHTING DESIGN Text discusses design of electric lighting systems which may include wiring and control aspects.

DAYLIGHT DESIGN Text discusses the design of daylight systems for either the enclosed atrium space or the space adjoining the atrium.

FIRE SAFETY Text discusses fire and smoke control systems including smoke ventilation, detection and firefighting systems and occupant escape routes.

STRUCTURE Text discusses structural design considerations unique, particularly relevant or important to atrium construction.

MATERIALS & ENVELOPE SYSTEMS Text discusses special requirements or opportunities pertinent to atrium design.

TRANSPORTATION Text discusses use and design of elevators and escalators.

ECONOMICS Text discusses cost implications of design strategies and/or general atrium design approach.

PLANTING Text discusses design considerations such as daylight, electric light temperature and humidity requirements, space and planting mediums.

CODES Test discusses atrium design as it relates or is restricted by planning and building codes.

GENERAL (DESIGN REVIEWS) Included in this category are general design reviews which are mostly "architectural" in content, usually general in nature and often fairly brief. Typically, they would deal with such topics as space planning, circulation and impact on the local environment. Unless paper deals specifically and in some depth with the design issues as articulated in the above classification, they will be referenced under this category.

Literature keywording is provided in matrix form (Table 5.1) where for each paper, identified by a reference number, the primary and secondary topics of the paper are identified. For those papers that deal with a specific building type, the last column in the matrix in reserved to indicate the building type according to the following classification.

HOTEL - code HOT
STORES & SHOPPING CENTRES - code RET
OFFICES - code OFF
RESIDENTIAL - code RES
SCHOOLS & UNIVERSITIES - code EDU
ALL OTHER BUILDINGS (not given above) - code OTH
MIXED USE BUILDING - code MIX

Text that is not building type specific will have no entry in this last column.

The actual title and source of the reference can be found by looking up the paper reference number in the Bibliography, section 5.3 (List of References).

REF #	Energy	HVAC	Elec Light Design	Daylight Design	Fire Safety	Structure	Materials	Transport	Economics	Modelling	Codes	Planting	General	Building Type
20													P	MIX
85													P	HOT
130													P	EDU
140													P	OFF
150													P	OFF
170													P	MIX
190													P	HOT
200													P	EDU
220													P	EDU
230													P	OFF
240													P	OTH
260													P	MIX
270													P	OFF
280													P	OFF

REF #	Energy	HVAC	Elec Light Design	Daylight Design	Fire Safety	Structure	Materials	Transport	Economics	Modelling	Codes	Planting	General	Building Type
290												P		OFF
300												P		OFF
305					P	S								RET
310	P													OFF
330	P			S						S				MIX
350												P		HOT
510												P		OFF
515	S	P			S									RET
520												P		OFF HOT
530	S	P	S											
540												P		OFF
550												P		OFF
555		S	S	P										OFF
600	S	P												OFF

P=Primary S=Secondary

TABLE 5.1
LITERATURE REWORDING

REF #	Energy	HVAC	Elec Light Design	Daylight Design	Fire Safety	Structure	Materials	Transport	Economics	Modelling	Codes	Planting	General	Building Type
645	S	S	S	P										OFF
755	S	S	S	S	S	S	S	S	S	S	S	S	S	OFF
1210	P													OFF
1250													P	OFF
1270													P	HOT
1280													P	MIX
1282										P				
1285													P	RET
1290													P	OFF
1291													P	RET
1295	P													OFF
1300													P	RET
1302													P	OFF
1305													P	OFF
1310	P							S						OFF
1320													P	OFF
1420		P												HOT
1430					P									HOT
1440					P									
1460	P				S									
1480	P									S				OTH
1490	P									S				RET
1495	P									S				OFF
1510	P									S				OFF
1512					P									RET
1520	P									S				OTH
1530	P									S				MIX
1585			P											RET

P=Primary S=Secondary

TABLE 5.1 (continued)

REF #	Energy	HVAC	Elec Light Design	Daylight Design	Fire Safety	Structure	Materials	Transport	Economics	Modelling	Codes	Planting	General	Building Type
1595						P								OFF
1655	S						P							RET
1665			P							S				RET
1690	S								P	S				OFF
1710													P	HOT
1755					P									
1760					P									HOT
1765				P		S	S							
1780					P									HOT
1790													P	RET
1810	S			S					P	S				OFF
1850	S	S				S		S	P					
1860	P									S				
1865		P												
1870		P												

REF #	Energy	HVAC	Elec Light Design	Daylight Design	Fire Safety	Structure	Materials	Transport	Economics	Modelling	Codes	Planting	General	Building Type
1890					P									
1910	P	S												EDU
1915													P	
1990					p									RET
1995					P									RET
2005			P											
2020	P	S		S					S	S				OTH
2030			P									S		
2040					S						P			
2050													P	
2055	S			S				S	S	P				OFF
2060													P	
3025	S	S		S						P				OTH
3085													P	
3095					P									RET

P=Primary S=Secondary

TABLE 5.1 (continued)

REF #	Energy	HVAC	Elec Light Design	Daylight Design	Fire Safety	Structure	Materials	Transport	Economics	Modelling	Codes	Planting	General	Building Type
3120	P													OTH
3180													P	OFF
3185					P									
3190													P	HOT
3210	P									S				OFF
3240	P									S				OFF
3350	S	S	S	S	S	S	S	S	S	S	S	S	S	
3360								P						
3365			P											RET
3370		P			S									OFF
3380		P			S									MIX
3390					P									MIX
3410	S	S		P					S	S				OFF
3440	S		P	S										OFF

REF #	Energy	HVAC	Elec Light Design	Daylight Design	Fire Safety	Structure	Materials	Transport	Economics	Modelling	Codes	Planting	General	Building Type
3480	P													OFF
3490													P	OTH
3500	P													OTH
3515													P	HOT
3570						P	S							
3600	P													
3675		P	S											RET
3680	P			S										
3690					P									
3730													P	OFF
3740													P	MIX

P=Primary S=Secondary.

TABLE 5.1 (continued)

JOURNAL	GROUP RESPONSIBLE FOR PUBLICATION
AIA Journal	American Institute of Architects, Washington, D.C.
Architectural Design	Standard Catalogue Co., London, U.K.
Architectural Forum	Billboard Publications, New York
Architectural Record	McGraw-Hill, New York
Architectural Review	Architectural Press Ltd., London
ASHRAE Journal	American Society of Heating Refrigerating and Air Conditioning Engineers, Atlanta, Ga.
ASHRAE Transactions	American Society of Heating Refrigerating and Air Conditioning Engineers, Atlanta, Ga.
BRE Digest & Fire Research Notes	Building Research Establishment, Garston, U.K.
Building Design & Construction	Cahners Publishing Co., Chicago
Building Services	Building Services Publications Ltd., London, U.K.
Buildings	
Canadian Architect	Southam Business Publications
Electrical Construction & Maintenance	McGraw-Hill, New York
Engineer News Record	McGraw-Hill, New York
Fire Journal	National Fire Protection Association
Heating, Piping, Air Conditioning	Reinhold Publishing, Stanford, Ct.
Interiors	Billboard Publications, New York
Lighting Design & Application	Illuminating Engineering Society, New York
Light & Lighting	Illuminating Engineering Society, London
Progressive Architecture	Reinhold Publishing, New York
Solar Age	Solar Vision Inc., Harrisville, N.H.

TABLE 5.2
PUBLISHING BODY OF JOURNALS REFERENCED IN BIBLIOGRAPHY

Note: All the above Publications are available at the Canadian Institute for Scientific & Technical Information (CISTI) Library, Ottawa